TP 14045E

PRV Field Trials – The Effects of Fire Conditions and PRV Blowdown on Propane Tank Survivability in a Fire

Prepared for

Transportation Development Centre
Transport Canada
TDC Contract: T8200-9-A521/001/XSD

by

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16. Abstract

When a tank holding propane is heated by fire, there is a chance that the tank will fail. The goal of this project was to study how different pressure relief valve (PRV) characteristics affect the behaviour of a propane filled pressure vessel in a fire. This project involved exposing pressure vessels containing propane to severe fire in order to study the role of the PRV.

Thirteen controlled fire tests were conducted on 1890 litre propane tanks in the summers of 2000, 2001, and 2002. The test tanks were instrumented with pressure transducers, lading and wall thermocouples, and an instrumented flow nozzle. A computer controlled PRV was used to control the pressure. High momentum liquid propane torches were used to heat the tank. PRV blowdown and fire conditions were varied in these tests, while all other input parameters were held constant.

The impact of the blowdown and fire conditions was determined by observing the nature of the failure, the time to failure, and a thermohydraulic response of the tank lading. The PRV blowdown behaviour and fire conditions affected the outcome of the fire impingement. It was found that an increase in the blowdown resulted in delayed failure, a lower fill level and stored energy at failure, and reduced hazards.

This study suggests that the PRV blowdown should be set as large as practically possible, while the PRV opening pressure should be set as low as practically possible.

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16. Résumé

Un réservoir de gaz propane soumis à l'action du feu est susceptible de rupture. Le projet avait pour but d'étudier l'influence des différentes caractéristiques des soupapes de sûreté sur le comportement au feu des réservoirs de gaz propane sous pression. S'agissant d'étudier le rôle de leur soupape de sûreté, des récipients de propane sous pression ont été exposés à un feu de grande intensité.

Treize essais de tenue au feu ont été menés en conditions contrôlées avec des réservoirs de propane de 1 890 litres durant les étés de 2000, 2001 et 2002. Les réservoirs essayés étaient munis d'instruments : capteurs de pression, thermocouples plongés dans le chargement et montés sur les parois du réservoir, appareils de mesure placés dans l'orifice de la soupape. Pour modifier les pressions, les chercheurs ont utilisé une soupape de sûreté commandée par ordinateur. Le réservoir a été chauffé à l'aide de chalumeaux au propane liquide à grand débit. Les essais se sont déroulés en conditions variables de chaleur par le feu et de détente de la soupape, tous les autres paramètres demeurant constants.

Les conséquences des conditions de feu et de détente ont été évaluées en fonction de la nature de la rupture, du temps de rupture et de la réaction thermohydraulique de la charge contenue dans le réservoir. Le comportement de la soupape durant sa détente et les conditions du feu ont influé sur les conséquences du contact des flammes. L'étude a révélé qu'un accroissement de la chute de pression à l'ouverture a retardé le moment de la rupture, fait descendre le niveau du contenu, réduit l'énergie stockée au moment de la rupture et causé moins de dommages.

L'étude donne à penser que la chute de pression à l'ouverture devrait être réglée à sa valeur la plus grande possible tandis que l'ouverture devrait se produire à la pression la plus basse possible.

17. Mots clés	18. Diffusion
essais au feu, gaz liquéfié sous pression, GPL, propane, récipient sous pression, wagon-citerne, soupape de sûreté, détente, chute de pression à l'ouverture, détente explosive de vapeurs de liquides en ébullition (BLEVE), perte de contenu, rupture sous contrainte thermique, échauffement localisé	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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Executive Summary

If a pressure vessel containing a pressure liquefied gas (PLG) such as propane is exposed to a fire, there is a chance the tank will rupture and possibly explode. A pressure relief valve (PRV) is often used to limit the allowable pressure within a vessel and can in some cases save a tank from thermal rupture. Some PRVs commonly supplied on commercial propane tanks, however, have shown significant variability and unpredictability in their behaviour. This report discusses controlled fire tests performed in the summers of 2000, 2001, and 2002 to study the effect of PRV behaviour on a pressure vessel engulfed in fire.

Some commercial PRVs have shown variability in all operating parameters, including start-to-discharge pressure, pop pressure, closing pressure, reseal pressure, mode of operation (cycle open and closed or simmer partially open), flow rate and blowdown. In this study blowdown is defined as the pop pressure minus the reclose pressure. The effect of some of these behaviour characteristics is obvious. A higher pressure in the tank will result in higher stress in the tank and will increase the chance of thermal rupture. The lower the flow capacity, the more difficult it is for the PRV to keep up with the vapour generation. This can lead to an increasing pressure even if the PRV is open.

The effect of the blowdown is not so obvious. It is important to know how variability in PRV blowdown affects tank survivability in a fire under various fire conditions. It was expected that large blowdown would result in a lower average tank pressure and this would lead to reduced stress and reduced energy stored in the tank. However, blowdown would also affect the vapour space temperatures and this could lead to increased material degradation in the tank wall.

Additional objectives of the tests included a need to learn more about the failure mechanism and the transition between catastrophic and non-catastrophic failures. Also it is always helpful to collect fire test data for computer model validation. There is also a current interest in insulation defects that can result in local heating of tanks. This test series has also provided some data on the localized heating of tank wall and how this can lead to tank thermal rupture.

A total of 13 propane tanks were thermally ruptured. In 2000, the main goal was to develop a test procedure and only three tests were performed. In this first test season the three tanks ruptured but did not result in a Boiling Liquid Expanding Vapour Explosion (BLEVE). In 2001, the majority of the data was collected as six tests were completed. In this test series all six tanks exploded. Four tests were performed in the final test series in 2002, which was used to fill in gaps in the data and verify previous results. All the tanks exploded in 2002.

Standard ASME code 1890 litre (500 US gal), steel, liquefied petroleum gas (LPG) tanks were filled 80% full of propane for the field tests. This tank size was selected because it ensures that large scale effects will be present (i.e. liquid temperature stratification, two-

phase swell, etc) and it allows for detailed instrumentation. Another scale factor was that the expected explosion could easily be accommodated at the test site.

The tanks were instrumented with 48 lading thermocouples, three pressure transducers, four wall thermocouples, and a nozzle thermocouple. High speed video, regular video, and still cameras were used to record the events. The tests were conducted at Defence R&D Canada – Valcartier in Quebec, Canada.

The standard mechanical pop action PRV was removed from the tank and replaced with a computer-controlled fast acting ball valve to give better control over the tank pressure. The opening pressure was set to 1.9 MPa (gauge, 275 psig) in each test, while the blowdown was varied between 5% and 45% of the set pressure. A smooth, machined, metered nozzle was used to choke the flow.

An array of liquid propane utility torches was used to simulate the fire conditions. Burners were directed at both the liquid wetted wall and the unwetted wall in the vapour space. The vapour space burners were used to weaken the tank and initiate failure. Either two or three burners were used on the vapour space. Four, eight, 10, or 12 burners were used to heat the lading on the liquid space.

Of the 13 tests performed, 10 resulted in a BLEVE. Five of the BLEVEs were Two-Step BLEVEs. The remaining three tests resulted in a non-BLEVE failure. The failure and hazards differed according to the fill in the tank at the time of failure and the way in which the tank opened up.

This report presents a wide range of data and analysis from the experiments. Vapour space wall temperatures, tank pressures, lading temperatures, and nozzle temperatures and pressures are presented. Average vapour and liquid temperatures, mass flow rate, liquid level, lading thermal energy, and thermal stratification have been calculated and are also presented.

It was seen, as expected, that the fire conditions have a significant impact on the test outcome. The size of the fire on the vapour space dictates the heat affected area and this influences the crack growth and the probability of a BLEVE. The mass flow rate through the nozzle depends on the heat input rate into the liquid lading. The fire distribution affects the temperature gradients and stratification within the tank and thus the fluid motion.

Tests with similar fire conditions must be compared when making conclusions with the data. Wall temperature behaviours for tests with similar fire conditions are very similar, showing very repeatable burner behaviour.

The data suggests that an increased blowdown is beneficial because it results in a lower average pressure and thus a lower average stress, lower average liquid temperature (closely tied to liquid energy), lower and earlier peak energy, and an increased stratification (also closely tied to liquid energy). Results from 2001 showed that larger

blowdown significantly improved the survivability of a propane tank by delaying failure. Larger blowdown resulted in a lower fill at failure and a lower energy available in the tank for hazards at failure. Results from 2000 and 2002 do not show that increased blowdown improves survivability. It is not clear why the 2000 and 2002 results do not show delayed failure. This may simply be differences in tank manufacture.

Results from all three years show that an increased blowdown results in lower energy at failure. This is a significant result because lower energy at failure reduces the chance of a BLEVE and also decreases the hazards.

This study suggests that the blowdown should be set as large as practically possible, while the opening pressure be set as low as practically possible. It is also recommended that standards reflect the important role of blowdown and that valves be manufactured so they have a predictable and repeatable performance.

The following are additional conclusions that were made from these tests.

i) tanks heated near the liquid level will pressurize faster than tanks heated near the tank bottom. This results in earlier activation of the PRV.

ii) the likelihood of a BLEVE is also affected by the severely heated length of the vapour space. The critical length that results in a BLEVE depends on the tank stress (i.e. pressure, diameter and wall thickness), the tank wall temperature and the liquid and vapour energy content at the moment of initial tank failure.

iii) in the tests with localized heating, tank failure took place when the hoop stress was around 150% of the material ultimate strength based on the minimum allowable tank material strength and the average temperature in the severely heated length.

The above conclusions are of direct interest to the study of insulation defects on tank-cars.

Sommaire

Lorsqu'un récipient contenant un gaz liquéfié sous pression, par exemple du propane, est exposé à des flammes, celui-ci est susceptible de subir une rupture et même d'exploser. Ce type de récipient est souvent équipé d'une soupape de sûreté destinée à limiter la pression intérieure à une valeur déterminée. Dans certains cas, la soupape peut même empêcher que le réservoir explose sous l'effet de la chaleur. Or, des soupapes montées sur des réservoirs de propane que l'on trouve dans le commerce ont fonctionné de manière assez variable et imprévisible. Ce rapport concerne les effets d'essais au feu contrôlés réalisés durant les étés de 2000, de 2001 et de 2002 dans le but d'étudier l'influence de la soupape de sûreté sur le comportement d'un récipient sous pression enveloppé par des flammes.

Des soupapes de sûreté de réservoirs du commerce ont présenté des différences pour tous leurs paramètres de fonctionnement, y compris le début de l'ouverture, la pression d'ouverture, la pression de fermeture, la pression de fermeture étanche, le mode de fonctionnement (cycle d'ouverture-fermeture ou battement en ouverture partielle), le débit et la chute de pression à la fermeture. Aux fins de la présente étude, la chute de pression à la fermeture est la différence entre la pression au début de l'ouverture et la pression à la fermeture. Certaines caractéristiques de fonctionnement produisent un effet évident sur la tenue du récipient sous pression. Le réservoir est soumis à une contrainte d'autant plus grande que la pression à l'intérieur est élevée, ce qui fait augmenter le risque d'éclatement causé par un phénomène thermique. Plus la capacité de débit de la soupape de sûreté est faible, plus l'évacuation des gaz sera difficile : la pression à l'intérieur pourrait augmenter même si la soupape est ouverte.

Les conséquences de la détente ne sont pas aussi évidentes qu'on voudrait le croire. On doit chercher à connaître comment la variabilité des paramètres de détente de la soupape influe sur l'aptitude du réservoir à survivre à différentes conditions de feu. On estimait qu'une chute de pression importante à la fermeture ferait baisser de beaucoup la pression moyenne dans le réservoir, avec, pour conséquence, une diminution des contraintes du réservoir et une réduction de la quantité d'énergie stockée. Or, la détente de la soupape de sûreté modifierait également la température du volume gazeux et cela pourrait entraîner une détérioration accrue de la paroi du réservoir.

Les essais visaient entre autres à recueillir davantage d'informations sur le mécanisme de rupture et sur la transition entre la rupture progressive et la rupture brutale. De plus, les données de tenue au feu ainsi recueillies pourront servir, au besoin, à valider un éventuel modèle informatique. Comme les chercheurs s'intéressent aussi aux défauts de calorifuge susceptibles de causer un échauffement localisé des réservoirs, les essais constituent également une source de données sur l'échauffement localisé des parois des citernes et sur la façon dont ce phénomène peut entraîner la rupture du réservoir sous contrainte thermique.

Au total, treize réservoirs de gaz propane ont été essayés au feu jusqu'à éclatement. Comme l'objectif principal pour l'année 2000 était de développer une procédure d'essai,

seulement trois essais ont été réalisés cette année-là. Les trois réservoirs ont éclaté, mais sans détente explosive de vapeurs de liquide en ébullition (BLEVE). La majorité des données ont été collectées durant l'été de 2001 avec l'achèvement des six essais, qui ont tous conduit à l'explosion des réservoirs. Quatre essais ont été réalisés durant la dernière campagne, en 2002, qui a servi à compléter les données manquantes et à valider les résultats précédents. Tous les réservoirs de la campagne de 2002 ont explosé.

Les essais, réalisés en vraie grandeur, ont porté sur des réservoirs de gaz de pétrole liquéfié, en acier, d'une capacité de 1 890 litres, conformes à la norme ASME et remplis à 80 p. cent de leur capacité. Cette grosseur a été retenue parce qu'elle produit des effets à grande échelle (p. ex. stratification des températures de liquide, expansion biphasique) en plus de permettre l'utilisation d'instruments de mesure perfectionnés. Le site de mise en œuvre pouvait facilement supporter les explosions que peuvent produire des essais en vraie grandeur.

Les réservoirs étaient équipés de 48 thermocouples placés dans la charge, de trois transducteurs de pression, de quatre thermocouples posés sur les parois et d'un thermocouple placé dans l'orifice de la soupape de sûreté. Pour enregistrer les essais, une vidéo ultra-rapide, une vidéo ordinaire et des appareils photographiques ont été utilisés. Tous les essais ont été réalisés à l'établissement R&D pour la défense Canada – Valcartier, Québec, Canada.

La soupape de sûreté standard à ouverture mécanique qui était montée sur les réservoirs a été remplacée par un clapet à bille réagissant plus rapidement, afin qu'il soit possible d'intervenir plus facilement sur la pression. Pour chacun des essais, la pression de détente a été réglée à 1,9 MPa (275 lb/po^2) au manomètre tandis que la chute de pression à la fermeture variait entre 5 p. cent et 45 p. cent. Pour réduire l'écoulement, on a utilisé un orifice mesuré à parois lisses usinées.

Une batterie de chalumeaux d'usage général au propane ont été utilisés pour simuler les flammes d'un incendie. Les buses des chalumeaux étaient dirigées sur les parties du réservoir en contact avec la phase vapeur et sur celles qui ne l'étaient pas. Pour chauffer la phase vapeur, on a appliqué deux et trois buses; pour chauffer la phase liquide, quatre, huit, dix et douze buses ont été utilisées. Le chauffage de la phase vapeur visait à affaiblir le réservoir et amorcer la rupture.

Sur les treize essais, dix ont produit un BLEVE, dont cinq étaient biphasiques. Quant aux trois derniers essais, ils ont aussi causé chacun une rupture, mais qui n'était pas due à un BLEVE. Les caractéristiques de rupture et les dommages étaient différents selon, respectivement, le niveau de remplissage du réservoir et le mode de rupture.

Le rapport présente un large éventail de données et d'analyses issues de l'expérimentation et portant sur la température des parois de la phase vapeur, la pression à l'intérieur du réservoir, la température du contenu, la température et la pression dans l'orifice d'évacuation de la soupape. Sont également indiquées les valeurs calculées de

températures moyennes des phases vapeur et liquide, le débit massique, le niveau du liquide, l'énergie thermique du chargement et la stratification selon les températures.

L'étude a révélé, comme il avait été prévu, que les conditions du feu ont une influence importante sur les résultats des essais. La dimension du feu appliqué au volume contenant la phase vapeur détermine la surface qui est surchauffée, ce paramètre agissant sur la progression des fissures et sur la probabilité d'occurrence d'un BLEVE. Le débit massique à travers l'orifice de la soupape de sûreté est fonction de la quantité de chaleur communiquée au contenu liquide du réservoir. La distribution des flammes influe sur les gradients et la stratification de température dans le réservoir et, par conséquent, sur le mouvement du fluide.

Des essais lors de conditions de feu similaires doivent être comparés au moment d'émettre des conclusions à l'aide des données. Des températures de paroi semblables ont été observées lors d'essais en conditions de feu similaires, ce qui permet de conclure que le comportement au feu peut être facilement reproduit.

Les données de ces essais semblent indiquer qu'il faut régler la soupape pour une plus grande chute de pression à la fermeture parce que cela contribue à donner une pression moyenne plus basse et produit donc une contrainte moyenne moins forte, une température moyenne de liquide moins élevée (en étroite relation avec l'énergie contenue dans le liquide), un pic d'énergie moins élevé, plus hâtif, ainsi qu'une stratification thermique plus marquée (aussi en rapport étroit avec l'énergie du liquide). Les résultats des essais de 2001 montrent qu'une chute de pression plus forte à la fermeture augmentait de façon significative les chances de survie d'un réservoir de gaz propane parce qu'elle en repoussait le moment de rupture : on a pu observer que le niveau du contenu était plus bas au moment de la rupture et que l'énergie disponible dans le réservoir était plus faible, cette dernière étant responsable des dommages causés par la rupture. Les résultats obtenus durant les essais de 2000 et de 2002 n'ont pas indiqué qu'une plus forte chute de pression contribuait à une meilleure probabilité de survie des réservoirs. On ignore cependant pourquoi la rupture des réservoirs n'a pas été retardée. L'hypothèse des écarts de fabrication est avancée.

Les résultats de ces trois années d'essais montrent cependant qu'une chute de pression plus marquée à la fermeture de la soupape a pour conséquence de réduire l'énergie libérée à la rupture. Cette constatation est significative puisque cela réduit la probabilité de l'occurrence d'un BLEVE et la gravité des dommages causés par un BLEVE éventuel.

L'étude dont il est ici question indique que la soupape de sûreté doit être réglée pour la chute de pression à la fermeture la plus élevée et pour la pression d'ouverture la plus basse. Il est également recommandé que les normes pertinentes tiennent compte de l'importance de la chute de pression et que les soupapes soient fabriquées pour donner une performance prévisible et reproductible.

D'autres conclusions peuvent être tirées de ces essais :

i) l'augmentation de la pression dans les réservoirs soumis à une chaleur appliquée près du niveau du liquide est plus rapide que pour une application près du fond du réservoir, et elle déclenche plus rapidement la détente de la soupape de sûreté;

ii) la probabilité d'un BLEVE dépend aussi de la longueur du volume qui contient la phase vapeur et qui est soumis à une chaleur intense. La longueur critique qui détermine la survenance d'un BLEVE est liée aux facteurs de contrainte du réservoir (p. ex. la pression, le diamètre et l'épaisseur de paroi), de même qu'à la température de paroi et à l'énergie du liquide et de la vapeur au début de la rupture;

iii) durant les essais avec application localisée de chaleur, la rupture est survenue lorsque la contrainte périphérique avait atteint environ 150 p. cent de la résistance maximale du matériau, cette dernière étant calculée d'après la résistance minimale admissible du matériau du réservoir et la température moyenne de la longueur soumise à une chaleur intense.

Enfin, les conclusions du projet présentent en outre un intérêt direct pour l'étude des défaillances du calorifuge des wagons-citernes.

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1.0 Introduction

This report describes the results from a series of fire tests that were carried out by the Mechanical Engineering Department of Queen's University in Kingston, Ontario. The work was completed to study the effect of Pressure Relief Valve (PRV) operating characteristics on fire engulfed vessels and was conducted as part of Transport Canada contract T8200-9-A521/001/XSD. The tests were conducted at the Defence Research and Development Canada – Valcartier (DRDC-Valcartier) during the summers of 2000, 2001, and 2002. VanderSteen (2002) gives some more details on the testing in the summers of 2000 and 2001 in a recent M.Sc. thesis.

1.1 Background

1.1.1 Loss of Containment Accidents

Pressure liquefied gases (PLGs) are substances such as propane that under atmospheric conditions are gases, but for transportation and storage are liquefied by pressurization. Storing and transporting PLGs is common and is usually very safe due to well established standards. However, if a vessel is punctured or experiences a loss of containment (LOC), there can be a large release in energy, which is capable of causing considerable damage.

With large numbers of PLG storage facilities and the high frequency of rail and road transport of PLGs, there is a great need to understand LOC accidents and to take preventive measures against them. Although pressure vessel rupture is not common, its devastating effects make it a very serious hazard and thus pressure containment research must continue to improve the safety of pressure storage of PLGs.

There are several events that will lead to a loss of containment accident, such as:

- severe corrosion
- material or manufacturing flaw
- mechanical damage
- malfunction of a pressure relief device in the event of over pressurization or overfilling
- exposure to fire

This report is focused on the fire exposure event.

When a pressure vessel is exposed to fire, two things happen simultaneously. It experiences elevated wall temperatures and loss of material strength. At the same time it experiences an increase in internal pressure, and thus an increase in the wall stress. This increasing tank stress and decreasing tank strength creates the risk of rupture. If the vessel has a pressure relief device such as a PRV, however, the operating pressure and stress is held below a pre-set level. But if a tank is severely weakened by fire, the stress may still exceed the weakened tank strength, resulting in tank failure.

There are three possible outcomes if a vessel containing PLG is exposed to fire:

1. The tank could empty its contents through the PRV or another safety device. This is desirable because tank failure is prevented but all the contents have been released to the surroundings.
2. The tank could experience a partial failure with a transient jet release. This can produce rocket effects and results in a very large release.
3. The tank could experience a total loss of containment and a catastrophic failure. This is often referred to as a boiling liquid expanding vapour explosion (BLEVE) and is considered to be the worst case scenario.

There have been many definitions for the acronym BLEVE since its first use. In this project a BLEVE is defined as a *physical explosion in which expanding vapour and boiling liquid is explosively released when a vessel containing PLG fails catastrophically*. It does not necessarily have to involve the vessel breaking into several fragments or the generation of a fireball.

Typically the hazards associated with propane BLEVEs are fire, explosion blast, and projectiles.

The exact outcome of fire engulfment depends on several factors such as:

- size, shape and design of the tank (including thermal protection)
- lading properties
- fill level
- PRV behaviour
- severity and location of the fire

One goal of researchers in this field is to understand why different outcomes occur at different times. Understanding this will help towards the ultimate goal of making PLG storage safer by preventing failure and minimizing or suppressing hazards when failure does occur.

1.1.2 The Pressure Relief Valve

The pressure relief valve, the most common device used to prevent or control pressure vessel failure, plays a very important role in the thermohydraulic behaviour of the lading. The energy stored in the tank at the time of failure plays an important role in the final outcome of fire engulfment and the PRV operation affects this energy storage (see Birk, 1996). Despite their importance in the outcome of fire engulfment, commercial PRVs show significant variability in operation, as seen in previous BLEVE and PRV testing (Pierorazio and Birk, 2000).

This earlier research showed that variability existed in all PRV operating parameters, such as start to discharge pressure, pop pressure, closing pressure, mode of operation (cycle open and closed or simmer open), flow rate, and blowdown. Blowdown is defined as the difference between the opening and closing pressure divided by the opening pressure.

$$Blowdown = \frac{P_{open} - P_{close}}{P_{open}} \tag{1.1}$$

In this project, blowdown will often be described using terms such as a small blowdown or a large blowdown. Small blowdown refers to a small difference between the opening and closing pressure, while large blowdown refers to a large difference between the opening and closing pressure.

The effect of the operating pressure of the PRV on a vessel engulfed in fire is obvious. A higher pressure in the tank will result in a higher stress in the tank and will increase the chance of thermal rupture. A higher pressure at the time of failure results in more energy available and increases the chance of a BLEVE.

Similarly, the effect of the PRV flow capacity on a fire engulfed vessel is fairly obvious. The lower the flow capacity, the more difficult it is for the PRV to keep up with the vapour generation. This can lead to an increasing pressure in the tank even if the PRV is open. A properly sized PRV should not allow the pressure to continue to rise in a fire engulfed tank.

It is desired to study the effect of the pressure relief valve blowdown on a PLG tank in a fire engulfment scenario and to determine if the variability matters.

1.2 Objectives

The main objective of this study was to better understand the effect the pressure relief valve blowdown has on how a propane tank behaves in a fire – from the time the heating starts to the time the event is over. Specific questions included:

- What is the relationship between the PRV blowdown and the survivability of a propane tank engulfed in fire?
- Can changing the PRV blowdown affect the type of failure experienced, if an engulfed propane tank thermally ruptures? Is there a range of fire conditions where the PRV blowdown can make the difference between a BLEVE or a non-BLEVE failure or no thermal failure at all?
- What is the role of the PRV blowdown on the hazards resulting from thermal rupture?

These three questions are all related and must be studied together. For example, the hazards are related to the type of failure and the type of failure depends on how quickly a tank fails once it is engulfed.

Additional objectives included:

- develop a deeper understanding of thermal ruptures and BLEVEs
- determine the relationship between the fire conditions and both the PRV and tank behaviour
- learn more about the transition from non-BLEVE to BLEVE failures
- learn more about the effect of localized heating
- collect data for computer model validation

In order to meet these objectives, it was decided to experimentally study fire-engulfed vessels and the effect of fire conditions and pressure relief valve blowdown. Thirteen fire tests were conducted in the summers of 2000, 2001 and 2002. In these tests, all parameters were held constant except fire conditions and PRV blowdown.

The specific objectives of the tests varied from year to year. A brief summary of the objectives for each of the three years of testing is given below.

1.2.1 2000 Test Series

The 2000 series was the exploratory series:
- develop detailed test procedures
- obtain basic data to plan future tests
- calibrate burner system

1.2.2 2001 Test Series

The 2001 series was the main test series:
- determine the relationship between PRV blowdown and tank behaviour in fire
- collect more data from fire tests

1.2.3 2002 Test Series

The 2000 series was the supplementary series:
- verify results seen in previous years
- solidify understanding and fill in holes in data set

2.0 Theory

The present study tries to add to the current state of knowledge by analyzing the role the PRV has on the survivability of a tank exposed to fire. This chapter presents relevant background theory.

2.1 Thermal Rupture

Fire exposure above the liquid level can lead to wall temperatures of 600-700°C or higher and significant material weakening. The internal pressure will lead to thinning of the walls in the weakened areas. Failure occurs if the wall becomes too thin and weak to contain the internal pressure and a pin hole forms. This pin hole usually grows to produce a finite sized crack or fissure. This initial crack usually appears axially on a cylindrical tank, perpendicular to the principal stress (hoop stress). This failure process is known as thermal rupture.

Propane tank thermal ruptures can be divided into two categories: finite failures and BLEVEs. A BLEVE occurs if the fissure travels the entire length of the vessel to fully open the section of the tank. The crack usually turns circumferentially around the tank ends, but in some cases the crack may go straight through the tank ends. If the crack stops before the tank fully opens, the failure is considered to be a finite failure. It is believed that if the initial failure exceeds a critical length, the tank will fail catastrophically (see Baum and Butterfield, 1979; Kielec and Birk, 1997). The critical length obviously depends on several factors, such as tank size, wall thickness, and material. If the crack does grow beyond the initial failure, the failure will become a blunt shear-type failure.

In some cases, two tanks with approximately the same initial crack size will fail in different ways. In their series of tests on 400 litre tanks, Birk et al (1997) attempted to explain why a BLEVE sometimes occurs and why a non-BLEVE or finite failure sometimes occurs. Birk and Cunningham (1994) produced a map of the failure conditions for all of the 400 litre tanks tested. This BLEVE map, shown in Figure 1, shows how the result of fire impingement depends on both the tank strength and the contained liquid energy. The burst pressure presented on the vertical axis was calculated using the ultimate stress of the tank material given the wall temperature at failure. As can be seen in the figure, tanks containing high liquid energy are more likely to BLEVE for a given tank strength. In order to minimize the chance of a BLEVE, the tank must rupture with minimum energy storage.

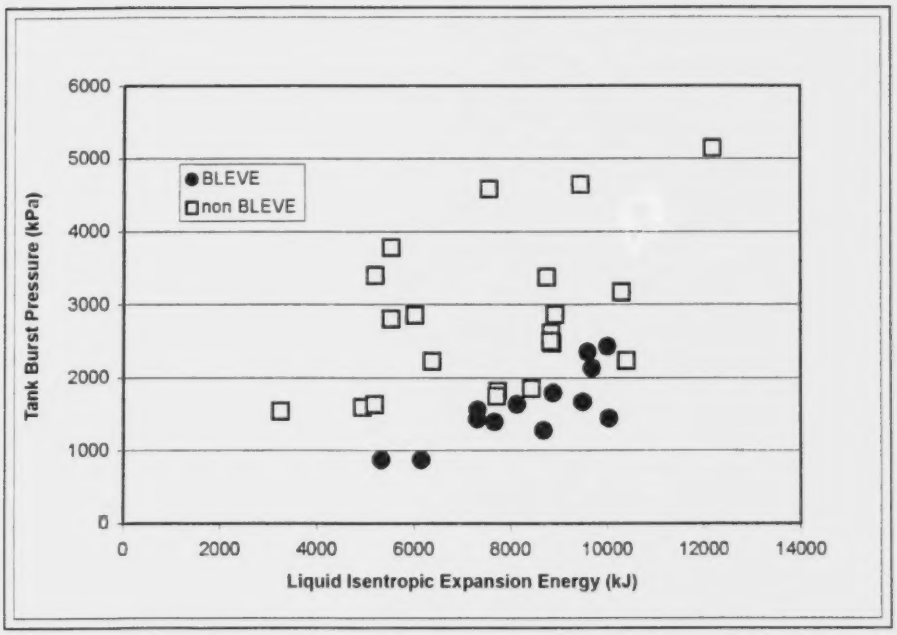

Figure 1: BLEVE Map for 400 L ASME Propane Tanks (Birk et al, 1997)

2.2 Pressure Relief Valves in Fire

Pressure relief valves are used to limit the pressure in a vessel if for some reason the pressure increases. Pressure increases may be caused by internal reactions, solar heating, overfilling and fire exposure. In most cases a tank will never be exposed to a fire. If it is, however, the PRV can in many cases delay failure, or in some cases save the tank from thermal rupture. A PRV by itself does not guarantee that a tank will be saved from failure in a fire. In fact, an operating PRV should be taken as a warning that something is wrong and the situation is dangerous. A PRV cannot protect a tank from failure if the tank is severely weakened by fire.

2.2.1 Pressure Relief Valve Operation

Most pressure vessels are equipped with a mechanically simple 'pop action' PRV. These valves are designed to unseat a spring loaded disk and start to discharge by some set pressure (plus or minus a tolerance). These valves are usually sized to provide a specified flow rate at a specified flow rating pressure. For example, the standard PRV used on the subject 1890 litre tanks had the following rating:

set pressure 1.72 MPa (250 psig)
start-to-discharge by 100-110% of set pressure
reclose and seal by 90% of start-to-discharge pressure
flow rating of 1.21 standard m^3/s air (2565 scfm) at 120% of set pressure

Figure 2 shows how a pop action PRV operates to expose the valve orifice. Once the pressure drops to no less than 90% of the set pressure, the valves are supposed to reseat and seal. A PRV cycle follows the following steps, as shown in Figure 3:

- Start-to-Discharge (Simmer)
- Pop fully open
- Discharge
- Reseat
- Reseal

The set pressures of the PRV are vital. In several fire tests by Birk et al (1994) involving 400 litre propane vessels with identical fire conditions, the pressure setting made the difference between a BLEVE and a non-BLEVE result. A lower opening pressure of 1700 kPa resulted in a non-BLEVE failure, while a higher set pressure of 2100 kPa resulted in a BLEVE. A lower setting of 1380 kPa resulted in no-failure. Birk (1996) states that the PRVs should be set as low as practically possible. Of course, too low of a setting is undesired as accidental releases can occur if a tank sits too long in the hot sun, for example.

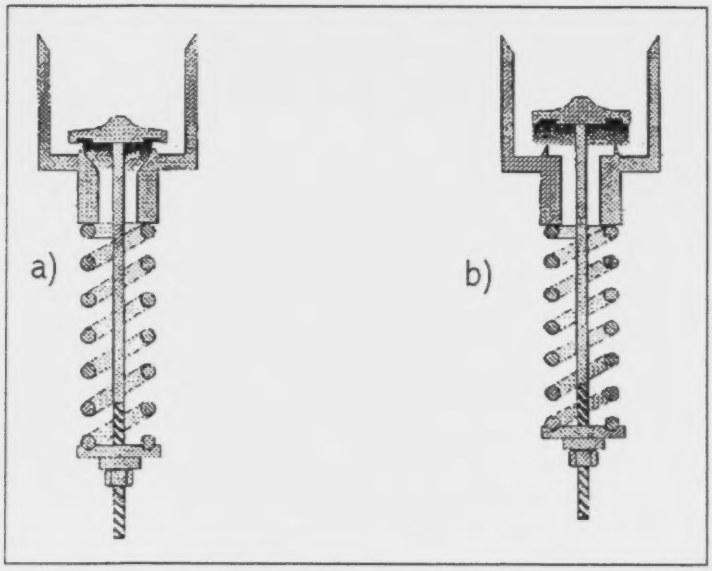

Figure 2: Pop Action Pressure Relief Valve a) Closed b) Open

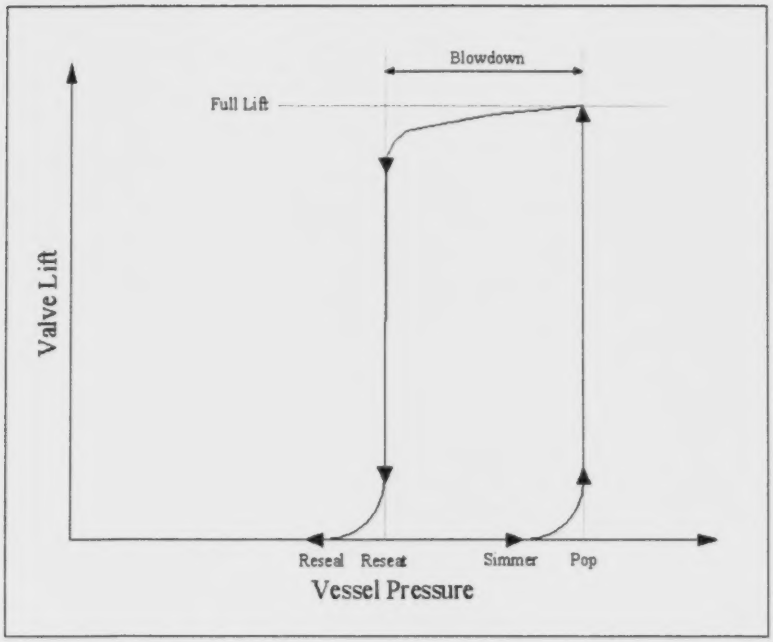

Figure 3: Typical PRV Cycle - Sealed, Start-to-Discharge (Simmer), Pop, Discharge, Reseat, Reseal

2.2.2 Variation in Pressure Relief Valves

Despite the importance of the PRV, past testing with standard PRVs has shown unpredictability in PRV behaviour. The performance of the PRVs used in the study by Birk et al (1994) of 400 litre propane tanks engulfed in fire was highly variable.

The initial opening pressure tended to be higher than the set pressure, while subsequent openings approach the set pressure. This was probably due to seals that had aged and stuck. Reseating of the valves was not always achieved, even when the seals were not destroyed by the heat of the fire. The blowdown was variable and the operating mode (simmer vs cycle) was unpredictable. Some valves simmered partially open even though all of the PRVs were designed to operate in an on/off cycling mode and to pop fully open by 120% of the set pressure. The variable behaviour of the PRVs made it very difficult to control the fire tests.

In an attempt to learn more about how PRVs behave in a fire, Pierorazio and Birk (2000) set out to determine the performance of three common valve designs relative to the governing standards and to each other. It was found that there is considerable variation in PRV performance between the different manufacturers, even though the valves were made to the same specification. Figure 4 shows the different blowdowns for the different valves tested. In this figure, blowdown is defined as the difference between pop pressure and reseat pressure. It was found that every valve tested failed the standard for which

they were stamped. (Pierorazio and Birk, 2000) These results spark a number of questions:

- Are the standards too strict?
- Does the variability in PRV performance matter?
- Should the standards be more strict since the PRV seems to play a very important role in fire situations?

This present study seeks to learn more about the effects of blowdown on tank survivability in a fire. More information on the PRVs used on the test tanks is found in Section 3.1.4 of the Field Testing Chapter.

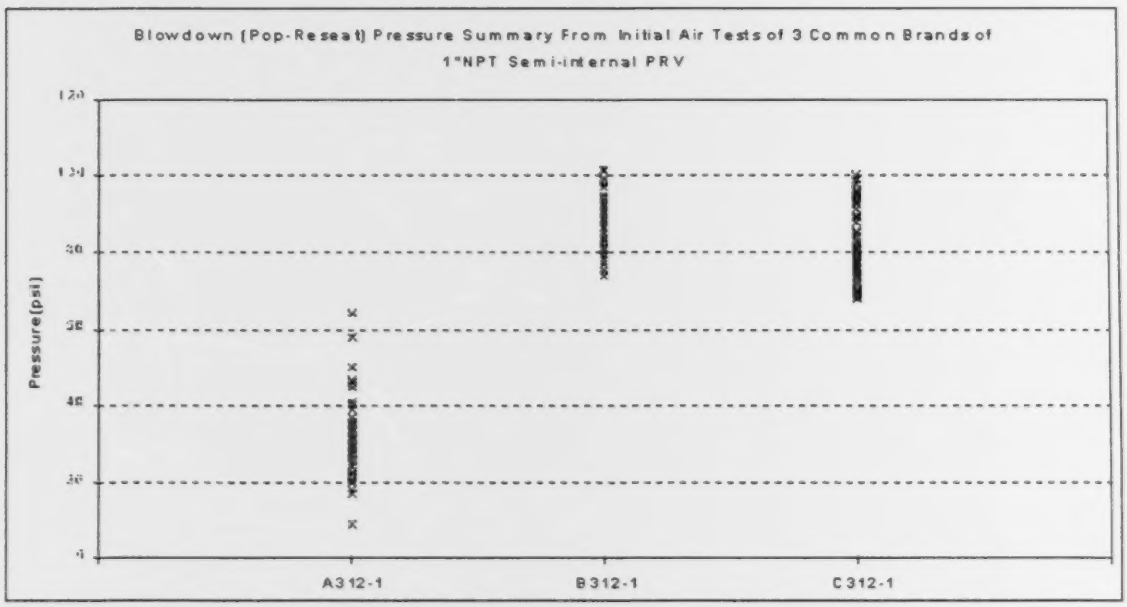
Blowdown (Pop-Reseat) Pressure Summary From Initial Air Tests of 3 Common Brands of 1"NPT Semi-internal PRV
Pressure(psi)
A312-1
B312-1
C312-1

Figure 4: PRV Performance from PRV Tests (Pierorazio and Birk, 2000)

3.0 Field Testing

The effect of the pressure relief valve blowdown on a tank's response to a fire was studied experimentally during the summers of 2000, 2001, and 2002. The project was headed by Dr. A. M. Birk of Queen's University, and was funded by Transport Canada. Thirteen instrumented propane tanks were exposed to controlled fire conditions and detailed data was collected. Three tanks were tested in 2000, six tanks in 2001, and the remaining four were tested in 2002. A general description of the field trials will be presented in this chapter. More detail is available in Appendix A.

3.1 Overall Test Layout

Before the PRV field tests were conducted, a conceptual test layout was designed. During the summer of 2000, the testing layout was further developed, while only minor modifications were made in the summer of 2001 and 2002.

3.1.1 Test Site

The Munitions Experimental Test Centre (METC) at the Defence Research and Development Canada – Valcartier, Quebec, was chosen to be the location of the field trials. This location was ideal for the testing because of its 800 metres by 600 metres plateau in the middle of a mountainous area virtually free of vegetation. The tanks and burner stands were placed on a concrete pad in the centre of the plateau. Approximately 35 metres from the concrete pad was an instrument bunker that was located behind a 0.61 metre thick concrete block wall. The instrument bunker contained all of the data acquisition equipment, cameras, computers, and other equipment. The computer controlled pressure relief valve and nozzle at the end of the tank and the propane supply tank approximately 50 metres from the test tank were also protected by thick concrete walls. An observation or remote bunker used for controlling and observing the tests was located approximately 370 metres from the tank, a distance that ensures personnel are safe from thermal radiation and blast hazards and greatly reduces the risk of projectile hazards. The general layout of the test site can be seen in Figure 5.

3.1.2 Test Tanks

Standard ASME code 1890 litre (500 US gallon), steel LPG storage tanks were used for the field testing. The tanks were designed and manufactured according to ASME Pressure Vessel Code (LPG service). The test tanks were horizontal steel cylinders with one longitudinal weld at the bottom of the tank and hemispherical end caps. A sketch of a test tank can be seen in Figure 6. The design gauge pressure for the test tanks at 46°C was 1.72 MPa (250 psi). A minimum wall thickness was specified for all of the test tanks, as indicated in the figure. Table 1 shows some more test tank specifications.

The burst pressure $\left[P_{burst} = \frac{2 \cdot \sigma_{ult} \cdot t}{D} \right]$ in Table 1 is calculated using an ultimate strength of 480 MPa at 46° C for SA-455 ASME Steel.

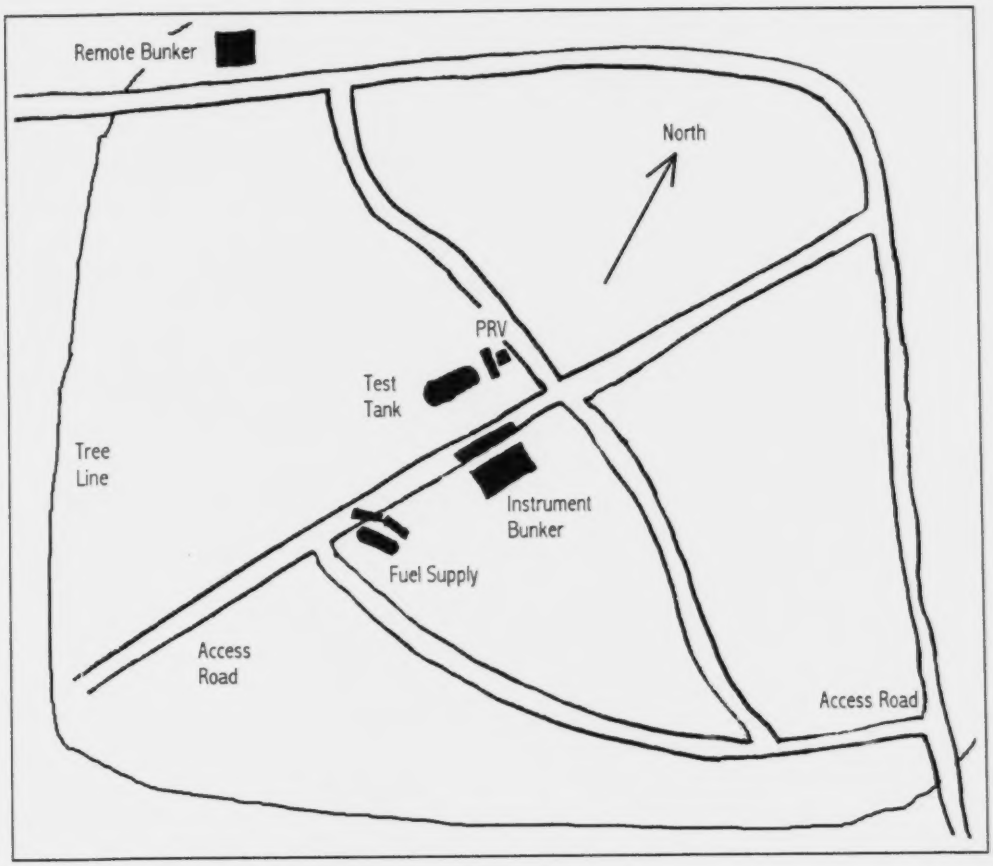

Figure 5: PRV Field Trials Site Map

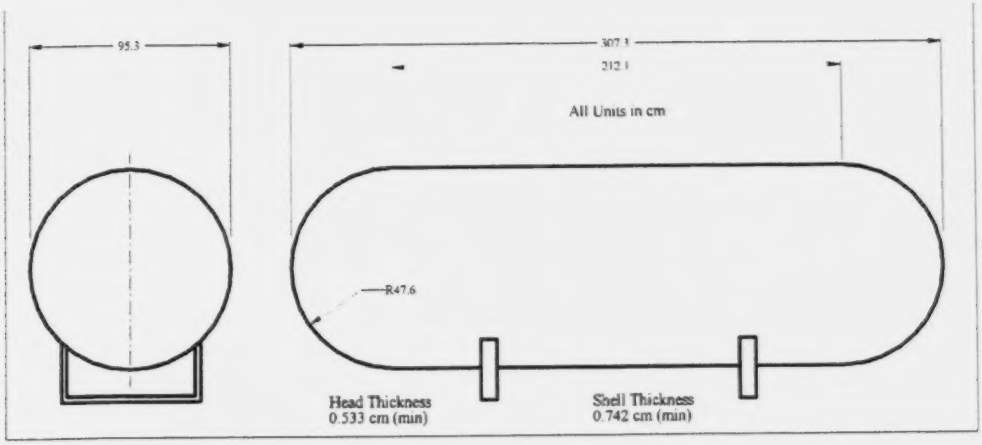

Figure 6: Standard ASME 1890 L Test Tank (From Manufacture's Drawing)

Specification	Property
Capacity	1890 Litre
Length	3.07 m (end to end)
Diameter	0.953 m
Minimum Wall Thickness-Shell	7.42 mm
Minimum Wall Thickness-Head	5.33 mm
Material-Shell	SA-455 ASME Steel
Material-Head	SA-285 gr.C ASME Steel
Design Pressure	1.72 MPa at 46°C
Calculated Burst Pressure	7.47 MPa at 46°C

Table 1: Test Tank Specifications

Modifications were necessary to accommodate five bundles of thermocouples and two pressure transducers to be attached to the tank from below. Seven 3/4" NPT couplings were welded onto the bottom of the tank for this instrumentation. In addition to the instrumentation couplings, a large coupling at the top of the tank was required for the pressure relief piping. For the three 2000 tests and the last two tests in 2001 (Test 01-5 and Test 01-6) this coupling was 38 mm (1.5 inches) in diameter, while the coupling was 51 mm (2.0 inches) in diameter for the first four 2001 tests and all 2002 tanks. This difference in coupling diameter did not affect the PRV flowrate, as a smaller converging nozzle choked the flow downstream of the coupling.

Propane was used as the lading because it is the most commonly stored and transported PLG, although trends seen in the results can be applied to other PLGs. Each tank was filled 80% full with commercial propane.

3.1.3 Burners

Fire testing of this type is usually carried out using liquid hydrocarbon fuelled pool fires. However, these are very difficult to control because of winds. This was not acceptable in this test series because the fire heat had to be repeatable from test to test. If the fires were not identical then the outcome would be affected by both the fire and the PRV blowdown. For this reason an array of burners was used instead of a pool fire.

The objective of the burner system was:

- to deliver heat to the liquid lading to cause rapid pressure rise and activate the pressure relief valve
- to deliver heat to the vapour space wall to weaken the tank and initiate tank rupture
- to deliver the heat as uniformly as possible over time during the duration of the test
- to deliver the heat in a repeatable way from test to test

An array of nominal 586 kW each (2 million BTU/hr) liquid propane utility torches were used to simulate conditions from a credible fire in order to accomplish these objectives.

The burners were nominally 586 kW, but only a small percentage (approximately 10%) of the energy actually went into the tank. Most of the heat was lost to the surroundings.

These burners were used because their high momentum jet made the heating rate consistent and repeatable, mimimizing the effect of external factors such as wind. Heat transfer from the fire to the tank in a high momentum jet is dominated by convection, while in a real engulfing fire situation, heat transfer is balanced between radiation and convection depending on scale, tank material and surface properties, and type of fire. (Birk, 1995) Using a pool fire would be more representative of real accident conditions, but a pool fire is not as consistent and repeatable.

The torches were aimed at both the liquid space and the vapour space, with the number of burners varied from 7 to 14 depending on the test. Fourteen burners was the maximum number of burners selected because 14 burners give a very similar net heat flux to the tank as a fully engulfing sooty fire at 816°C (1500°F). This temperature (816°C) is the typical fire temperature seen in a simulated pool-fire test as specified by the CGSB standards (CAN/CGSB-43.147-97 Appendix D). See Appendix A for more details.

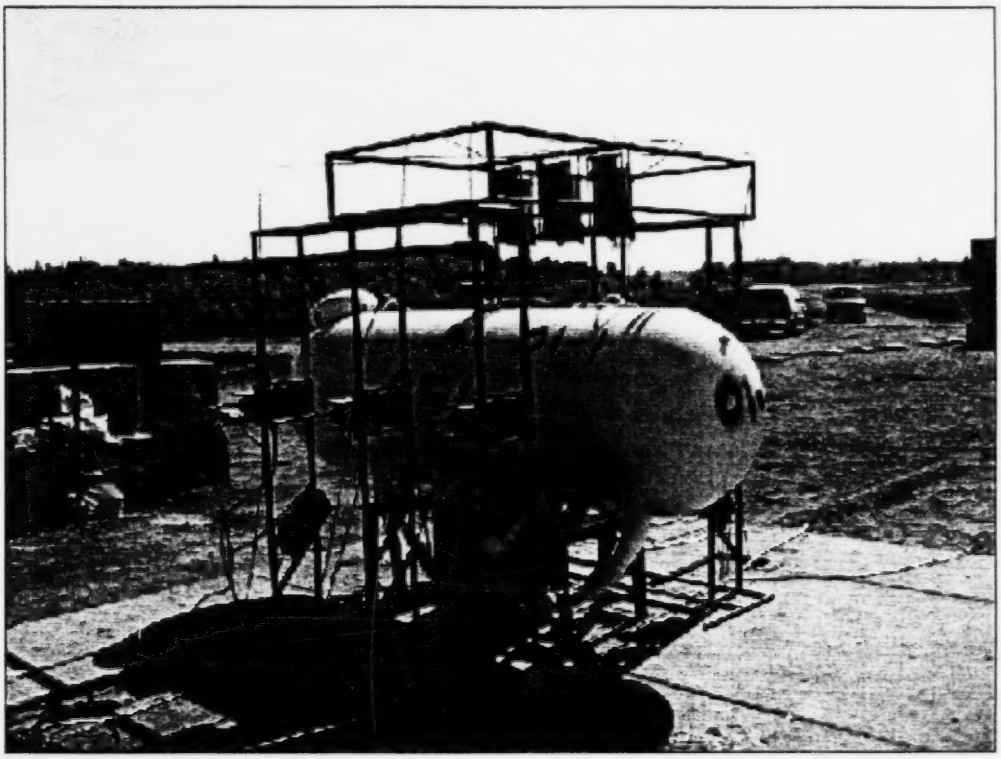

Figure 7: Test Set-up Showing Burner Locations for 13 Burner Tests

The burner nozzles and propane supply pressure were kept constant through all of the tests, except the last two tests in 2002 when the fuel supply pressure at the fuel supply tank was dropped from 40 psi to 25 psi. The exact fuel pressure at each burner nozzle depended on the number of burners used. The larger the number of burners, the higher the propane flow rate and the larger the pressure drop through the piping.

Figure 7 shows a photograph of a tank with the burner stands and burners in place. In the test shown in this photo, 13 burners are used.

The burner system was tested in the laboratory before the field work was completed. Appendix I shows some results from the laboratory work.

3.1.4 Pressure Relief System

Since the primary goal of the field testing was to determine the role of the pressure relief valve, it was vital to have good control over the valve behaviour. Since this was not possible with commercial PRVs, the original PRV (Figure 8) was removed and replaced with a computer controlled valve. This required bringing a pipeline off the top (vapour phase) of the tank and using a fast acting valve to control flow out of the tank. An instrumented flow nozzle was used on the outlet side of the valve. Because of the potential for large explosions and the expense of the valves and nozzle, the pipeline was routed behind a concrete wall. A sketch of the layout can be seen in Figure 9.

Figure 8: Original Tank PRV (250 psig, 1" diameter, 2565 scfm)

3.1.4.1 Original Pressure Relief Valve

It was important for the pressure relief system to mimic the original pressure relief valve while maintaining complete control over the valve operation. Figure 8 shows a photo of one of the original PRVs that would have been installed on the test tanks.

Some of the specifications of this valve are below:

- Set Pressure = 250 psig (1.72 MPag)
- Size = 1 inch (25.4 mm) NPT
- Flow Capacity = 2565 standard cubic feet per minute (4358 m^3/hour) of air at 20% overpressure (300 psig or 2.07 MPag)
- Liquefied Petroleum Gas Safety Relief Valve
- Stamped by the Underwriters' Laboratories Inc. (ULC/ORD-C132-1992)
  - -Set pressure tolerance is 0 to 10% on first opening (first opening is defined as start-to-discharge pressure)
  - -Valve must pop fully open by 120% pressure in order to give full capacity flow
  - -Resealing must occur by at least 90% of start-to-discharge pressure
  - -Subsequent openings must be greater than 85% of initial start-to-discharge pressure
  - -Subsequent resealing must occur by at least 80% of start-to-discharge pressure

3.1.4.2 Computer Controlled Pressure Relief Valve

A rapid acting valve was required to keep up with the changing pressure, especially for the tests with small blowdown. The valve used was a normally closed, full port ball valve with a pneumatic, double acting actuator and a 110 VAC solenoid.

The control system used a pressure signal from a pressure transducer located on the bottom of the tank, as indicated by P1 in Figure 9. A second pressure transducer, P2, was placed in the piping between the tank and the valve. The reading from this valve was used as a redundant measurement of tank pressure when there was no flow through the PRV piping. When the valve was open or cycling, this pressure reading gave insight into the response of the system and pressure losses through the piping. A third pressure transducer, P3, was placed at the nozzle. This was used primarily for determining the mass flow through the nozzle, but also provided insight into losses through piping.

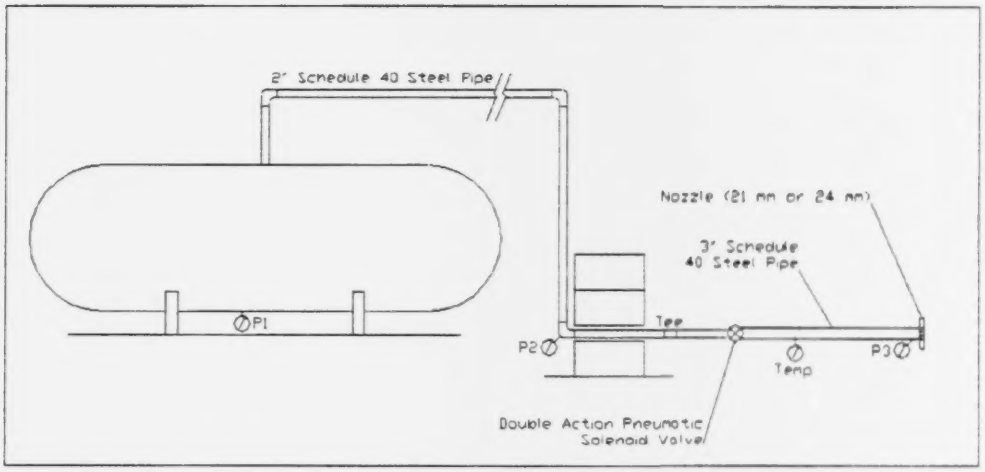

Figure 9: PRV, PRV Piping, and Nozzle Sketch

The field tests required the pressure relief valve to open when the tank pressure reached a set pressure and to close again when the pressure dropped to a second, lower set pressure. In all 13 tests, the simulated PRV was set to open at a gauge pressure of 1.9 MPa (275 psi), while the closing pressure was varied from 95% to 55% of the opening pressure (i.e. blowdowns of 5% to 45%).

This opening pressure was 10% higher than the set pressure marked on the valve: 250 psi (1.72 MPa). This opening pressure was selected because the actual, original pressure relief valves were stamped by the Underwriters' Laboratories of Canada, who specify that the start-to-discharge pressure shall not be more than 110% of the set pressure marked on the valve, as mentioned above. (ULC/ORD-C132-1992) This opening pressure was considered representative of real valve opening pressures.

3.1.4.3 PRV Flow Capacity

The PRV piping and metered nozzle were designed to be representative of an actual PRV in terms of flow capacity. The nozzle used at the end of the pressure relief piping was designed for choked flow, just like an actual PRV. A smooth converging nozzle with a diameter of 24 mm was used for the first three tests in 2000 and a nozzle diameter of 21 mm was used for the remaining tests. Figure 10 shows the nozzle with steam flow.

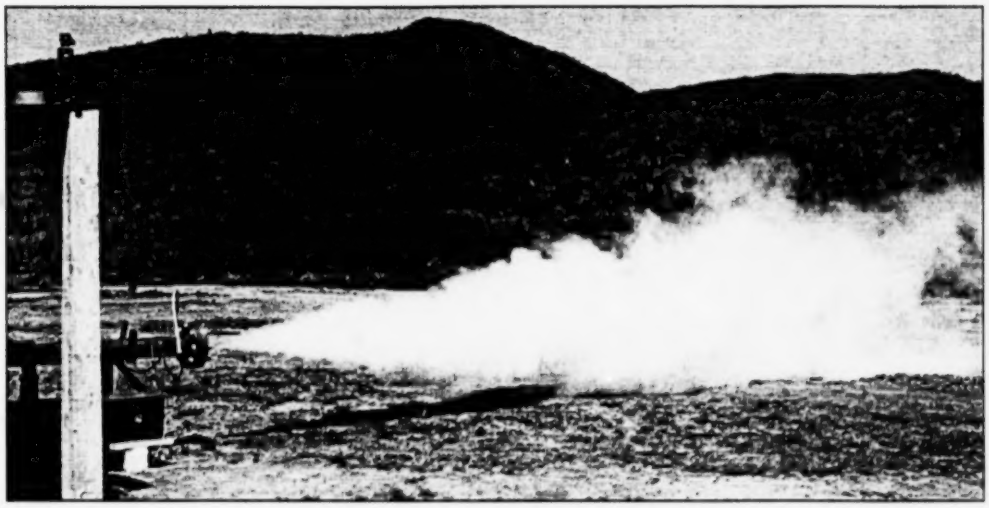

Figure 10: Converging Nozzle (21 mm)

As mentioned above, the valve was rated for 2565 scfm at 20% overpressure (2.07 MPa). Using the same valve, it can be calculated that the flow rate of propane at 1.90 MPa and 150°C (typical conditions) would be 1.35 kg/s. At this rate the tank would empty in approximately nine minutes. Appendix A shows that the mass flow rate ranged between 1.45 kg/s and 1.1 kg/s during the tests. These values are comparable.

Refer to Appendix A for more details of the pressure relief system.

3.2 Instrumentation and Control

3.2.1 Instrumentation

Each test tank was instrumented with 48 sheathed lading thermocouples, one static pressure transducer, one high-speed transient pressure transducer, and four wall thermocouples. The lading thermocouples were contained in five bundles with each bundle containing a full range of thermocouple lengths. Figure 11 shows a sketch of the location of the lading thermocouples. The centre bundle (Bundle 1) was located directly below the pressure relief outlet pipe. Bundles 2 and 3 were located at the two ends of the tank, with Bundle 2 being below the vapour space burners. The large number of thermocouples was used in the lading in order to better understand the temperature gradients and thermal stratification. Each thermocouple represents a specific fill level, as shown in Table 2 for Bundle 1. See Appendix B for more information on thermocouple locations.

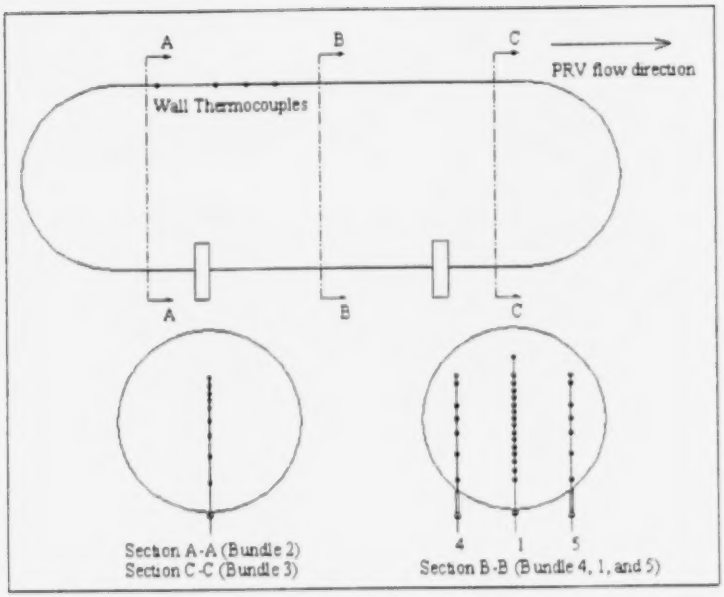

Figure 11: Lading and Wall Thermocouple Locations

Thermocouple	% Fill	Location
T0	90	Highest
T1	80	
T2	75	
T3	70	
T4	65	
T5	60	
T6	55	
T7	50	
T8	45	
T9	40	
T10	35	
T11	30	
T12	25	
T13	20	
T14	15	
T15	10	Lowest

Table 2: Thermocouple Locations (Bundle 1)

The tank wall in the vapour space was instrumented with four unsheathed thermocouples, located directly below the vapour space burners, as shown in Figure 11. The wall thermocouples were installed using the following procedure:

- A 1 mm hole was drilled into the tank wall approximately 1.5 mm deep.
- The two thermocouple leads were inserted into the hole.
- A flat punch was used to deform the tank wall material around the hole to firmly capture the thermocouple wires and form a junction.
- The thermocouple lead wires were carefully taped to the tank wall using aluminum tape.
- The thermocouples (junction and lead wires) were covered with a 13 mm thick by 30 mm wide strip of ceramic insulation. This insulation was covered by a 3 mm thick by 50 mm wide channel of steel.

This procedure was used to protect the thermocouple wire from the fire and has been shown in the laboratory to give accurate wall temperatures until the wall distorts. Significant distortion and bulging occur below the vapour space burners before tank failure, which usually separates the junctions from the tank wall, and results in a sudden increase in the thermocouple reading.

It is important to note that the tanks never failed at the holes that were drilled for the thermocouples.

Table 3 summarizes the instruments used in each test.

Measurement	Device	Quantity
Lading Temperature	Type K Thermocouple (3.175 mm, stainless steel, sheathed)	48
Tank Wall Temperature	Type K Thermocouple (24 gauge, unsheathed)	4
Tank Pressure	3.45 MPa (500 psi) Pressure Transducer	1
PRV Pipe Pressure	3.45 MPa (500 psi) Pressure Transducer	1
PRV Nozzle Pressure	3.45 MPa (500 psi) Pressure Transducer	1
PRV Nozzle Temperature	Type K Thermocouple (3.175 mm, stainless steel, sheathed)	1
Transient Tank Pressure	Piezoelectric Pressure Transducer	1

Table 3: Instrumentation List

Still photography, video, and high speed video (500 frames/second) were also used to collect data during the fire tests. Three camera shacks were located at various points around the tank, each with an SLR camera and a video camera. A video camera and the high speed camera were in the instrument bunker, viewing the event through a thick piece of plexiglass. Still cameras and a video camera were also located at the remote bunker,

370 metres from the test tank, along with a high powered, 30x telescope for the test personnel to use during the tests.

3.2.2 Data Acquisition System and Control

Data acquisition and control was accomplished with two methods.

1. A PC-based data acquisition system was used for the low frequency measurement recording and for all process control. The data acquisition card was a Sciemetric System 200 with 96 input channels, a solid-state relay module, and a digital input/output board. All static pressure and temperature measurements were digitally recorded using the Sciemetric System. The pressure transducers and the thermocouple in the nozzle were sampled at a rate of 10 Hz, while all other thermocouples were sampled once per second.
2. High frequency measurements were recorded using a Racal V-Store high speed FM type analog VHS tape recorders.

The Sciemetric System was controlled using LABVIEW programmed logic and was used to accomplish the following control tasks, in addition to recording the temperature and pressure measurements:

- Control propane burner ignitors.
- Control a shut off valve for the propane burner's fuel supply.
- Control pneumatically operated valves used for the tank pressure relief. During the tests, the control system used the pressure signal from the pressure transducer on the tank to determine when to open and close the main valve.
- Digitally record when the pressure relief valve was open and when it was closed. Using this information and the recorded nozzle temperature and pressure, the PRV mass flow rate could be calculated.
- Trigger the high speed FM tape recorder.

Necessary hardware for data acquisition and control was located in the instrument bunker (See Figure 5), but by using pcAnywhere software (Symantec) and a well protected fibre optic network cable, the tests were controlled completely from the remote bunker.

In the case of a loss of power and control, a normally open, pneumatic valve was placed off the tee shown in Figure 9. On the other side of the valve, a standard 1.72 MPa (250 psig) PRV was located. During testing, the normally open valve was energized so no fluid would flow through the conventional PRV, but if power was lost, the pneumatic valve would open and the conventional PRV would be available to control the tank pressure.

Appendix J gives more information on the data acquisition software.

3.3 Testing Technique

3.3.1 Test Sequence

The following procedure was used for each of the nine tests:

- The tank, burner stands, and required number of burners were located.
- Instrumentation was installed and cables were protected with ceramic insulation wherever possible.
- The tank was pressure tested for leaks using air from an air compressor at 689 kPag (100 psig).
- The air was vented through the converging nozzle by opening the pneumatic valve.
- The tank was purged of air and then filled to approximately 80% capacity with commercial propane.
- The air compressor, receiver, and lines were charged to 689 kPag (100 psig) for the main solenoid valve.
- The burner fuel lines were pressurized to 276 kPag (40 psig).
- The data acquisition system and recorders and cameras were powered up.
- Test conditions (i.e. blowdown) were programmed into control logic. An opening pressure of 1.9 MPag (275 psig) was used in all 13 tests.
- Video cameras, high speed video, and low speed FM recorder were started.
- Personnel were moved to the remote bunker.
- Data recording on the Sciemetric System was initiated.
- The propane burners were ignited.
- High speed FM recorder was started approximately seven minutes into test.
- Still cameras were triggered when tank failure began (once tank started to open).
- After tank failure, the burner fuel was shut down, and video cameras and data recording were stopped.
- Data was recorded until the tank failed.

Appendix J gives some checklists that were used in the field. These checklists give more information about the test sequence.

3.3.2 Test Matrix

The first three tests were conducted during August and September of 2000. Test 00-1 was the baseline test in 2000; it used a blowdown of 20% and included 14 burners. All 12 liquid space burners were used and only two burners were used on the vapour space. Test 00-2 was set up identically to Test 00-1, except it had a reduced blowdown of 5%. The last test, Test 00-3, was like Test 00-1, except it was run at reduced heating, with the four burners at the bottom removed, leaving it with eight liquid space burners. None of these tests, as will be explained in Section 4.1, resulted in a BLEVE.

For the next test series in 2001, several adjustments were made in an attempt to bring the tank failure closer to the transition between a BLEVE and a non-BLEVE failure. Another vapour space burner was added to increase the severely heated zone, and thus made the heated length and initial fissure larger. Also, in order to cause failure with more energy storage, the energy input rate and thus the energy (and mass) output rate had to be decreased. To accomplish this, the two end burners were removed, and the baseline tests in 2001 were completed with 10 liquid space burners. A more extreme range of blowdowns was used in 2001 in order to accentuate the effect of the PRV blowdown. Finally, the flow nozzle was changed from 24 mm to 21 mm for the 2001 tests in order to more closely mimic an actual PRV. The PRV nozzle size was a secondary variable since it only affected the PRV cycling frequency and not the tank pressure limits or total mass flow. (Appendix A gives details on some of these design changes.)

	Vapour	Liquid Burners			Blowdown	Fuel Pres
	Burners	Mid	Bottom	Ends	(%)	(kPag)
Test 00-1	2	6	4	2	20	276 (40psig)
Test 00-2	2	6	4	2	5	276
Test 00-3	2	6	0	2	20	276
Test 01-1	3	6	4	0	30	276
Test 01-2	3	6	4	0	5	276
Test 01-3	3	6	4	0	30	276
Test 01-4	3	6	4	0	5	276
Test 01-5	3	6	4	0	45	276
Test 01-6	3	0	4	0	5	276
Test 02-1	2	0	4	0	5	276
Test 02-2	2	0	4	0	30	276
Test 02-3	2	0	4	0	30	172 (25psig)
Test 02-4	2	0	4	0	5	172

Table 4: Variable Input Parameters

Test 01-1 and Test 01-3 were set up identically, each completed with 13 burners and a 30% blowdown. The input parameters in Test 01-2 and Test 01-4 differed from Test 01-1 and Test 01-3 only in the fact that they each used a 5% blowdown. Test 01-5 was an extreme blowdown test, using a blowdown of 45%. Finally, in Test 01-6, the only liquid space burners used were the four bottom burners. All of the tests with three vapour space burners BLEVEd, as described in Section 4.1.

The tests in 2002 were modified slightly in order to again bring the tank failure closer to the transition between a BLEVE and a non-BLEVE. They were intended to be repeats of Test 01-6 with two vapour space burners instead of three, that is with only the four bottom burners. Only four liquid space burners were used so that the tank would have a lower vapour generation rate, thus a lower mass flow rate and thus higher fill at failure.

A higher fill at failure means a higher chance of a BLEVE. The intention was to cause a BLEVE failure with a small heated zone (only two vapour space burners) like in 2000. It was hoped that perhaps with this fire condition, changing the blowdown could make the difference between a BLEVE and a non-BLEVE failure.

	PRV Setting (MPa)	Nozzle (mm)	Initial Volume (L)	PRV Fitting (mm)	Wind	Initial Temp (°C)
Test 00-1	1.90	24	1460	38		18
Test 00-2	1.90	24	1460	38		12
Test 00-3	1.90	24	1460	38	> 21 km/h	17
Test 01-1	1.90	21	1460	51	15 km/h E	24
Test 01-2	1.90	21	1460	51	12 km/h SW	13
Test 01-3	1.90	21	1460	51	12 km/h N	19
Test 01-4	1.90	21	1460	51	13 km/h NW	20
Test 01-5	1.90	21	1460	38	8 km/h NW	20
Test 01-6	1.90	21	1460	38	6 km/h NE	18
Test 02-1	1.90	21	1460	51	5 km/h E	11
Test 02-2	1.90	21	1460	51	4 km/h SE	22
Test 02-3	1.90	21	1460	51	9 km/h W	22
Test 02-4	1.90	21	1460	51	7 km/h SW	27

Table 5: Other Input Parameters

Tables 4 and 5 summarize the input parameters used in the test series. Table 4 shows the variable parameters, while Table 5 shows some of the remaining parameters.

4.0 Results and Discussion

This chapter summarizes the data collected in the 13 tests and discusses some of the relevant calculations completed using this data. Appendix E presents a more comprehensive compilation of the test results.

4.1 General Observations

All three tests conducted in the summer of 2000 resulted in finite failures, while each of the six tests completed in 2001 and each of the four tests in 2002 resulted in a BLEVE. The time to failure, thermohydraulic response, and energy available at failure all varied from test to test depending on the different input parameters. Appendix C contains more general information and data on the 13 tests.

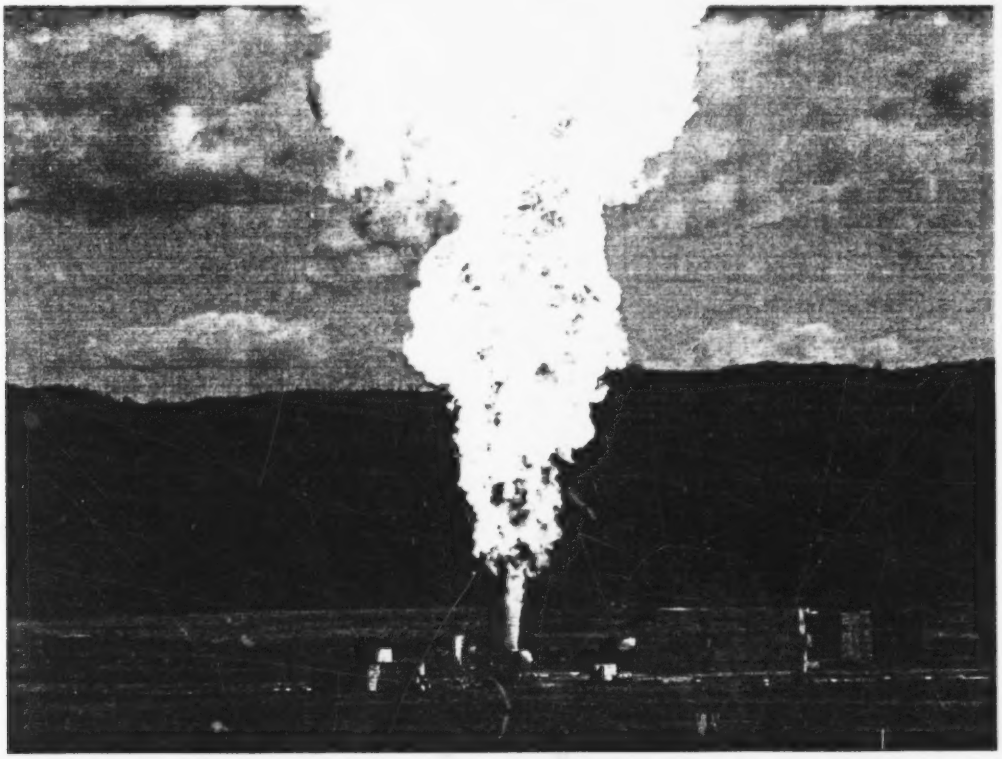

Figure 12: Test 00-3 Jet Release

4.1.1 2000 Test Results

Table 7 summarizes the 2000 tests.

Even though all three tanks in 2000 released their contents with a two phase jet upon failure, each failure was unique. The most energetic failure, Test 00-1, experienced a large 690 mm failure along with a massive jet. A fireball formed from the released propane and the powerful jet caused the tank to roll off of its stand, as shown in Figure 13. The small blowdown test of 2000, Test 00-2, failed later into the test and with less energy than the first test. It had a failure length of 215 mm with a small jet flare release and no fireball. The reduced heating test, Test 00-3, lasted the longest in the fire, but like Test 00-1, it experienced a large finite failure (550 mm) and a massive jet. Figure 12 shows a transient jet release from Test 00-3.

Figure 13: Tank 00-1 After Thermal Rupture and Jet Release

4.1.2 2001 Test Results

Table 8 summarizes the 2001 tests.

Similarly, even though all 6 tests in 2001 failed catastrophically with a BLEVE, each failure was unique. Test 01-2 and Test 01-6 were the most energetic BLEVEs, breaking

windows and knocking things off the tables in the instrument bunker 35 metres away. The increased blowdown test, Test 01-5, was the longest lasting test, and based on qualitative observations, was the least energetic at failure. Figure 14 shows the fireball produced in Test 01-1. Figure 15 shows the totally destroyed tank after a different BLEVE.

Figure 14: Test 01-1 Fireball

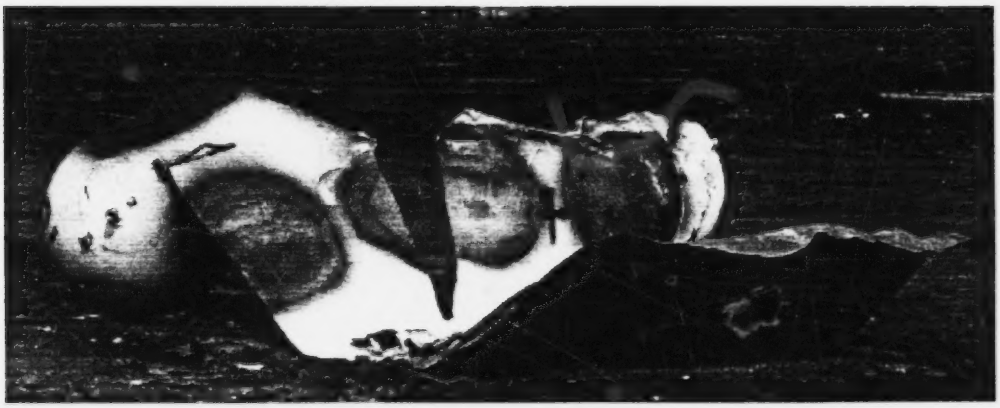

Figure 15: Flattened Tank of Test 01-4

4.1.3 2002 Test Results

Table 9 summarizes the 2002 tests. Table 6 summarizes some of the general observations from all the tests.

The goal for the 2002 tests was to find a fire condition that was very close to the transition between a BLEVE and a non-BLEVE failure for the test tanks where perhaps blowdown could make the difference between a BLEVE or a non-BLEVE failure. Despite this, all four tanks suffered a total loss of containment and BLEVE. Again, each test failed in a unique manner. Figure 16 and Figure 17 show two different tanks at the end of the test.

Test 02-1 and Test 02-2 both failed at approximately the same time with the same fill. Both tanks failed with slow two-step, energetic BLEVEs. A two-step BLEVE is one where the tank fails with a finite crack and initially there is only a jet release. This jet lasts a few seconds and then the crack is re-started and the tank fails catastrophically to generate a BLEVE. It is believed that the pressure transient in the tank, due to powerful flashing of the liquid, is the cause of the crack being restarted.

The first two tests of 2002 failed earlier and more energetically than anticipated so the propane burner supply fuel pressure at the supply tank was decreased from 276 kPa (40 psi) to 172 kPa (25 psi) for the final two tests. As a result, Test 02-3 and Test 02-4 lasted about a minute longer than the first two tests on average.

	Blowdown (%)	Time to Failure (min)	PRV Cycles	Type of Failure	Fill at Failure (%)
Test 00-1	20	13.0	16	Large Finite Failure	14
Test 00-2	5	13.5	91	Small Finite Failure	20
Test 00-3	20	17.2	28	Large Finite Failure	17
Test 01-1	30	15.2	9	Two Step BLEVE	17
Test 01-2	5	10.8	69	Two Step BLEVE	35
Test 01-3	30	15.6	11	Fast BLEVE	13
Test 01-4	5	12.4	82	Fast BLEVE	21
Test 01-5	45	16.3	4	Fast BLEVE	12
Test 01-6	5	10.0	38	Two Step BLEVE	49
Test 02-1	5	9.4	29	Two Step BLEVE	51
Test 02-2	30	8.7	2	Two Step BLEVE	52
Test 02-3	30	10.8	2	Fast BLEVE	53
Test 02-4	5	10.7	29	Fast BLEVE	61

Table 6: Test Results

Compared to the 2000 and 2001 tests, the tanks failed early in 2002. Also, unlike the tests in 2000, the tanks all BLEVEd with only two vapour space burners. Upon further

analyzing the tanks, it was determined that the tanks in 2002 were significantly thinner than the previous tanks. While the tanks were all approximately 7.7 mm thick in 2000 and 2001 tests, the 2002 tanks were all approximately 7.1 mm thick. This unfortunately added another unplanned independent variable. This can explain the earlier failure and in part explain why all 2002 tanks BLEVEd.

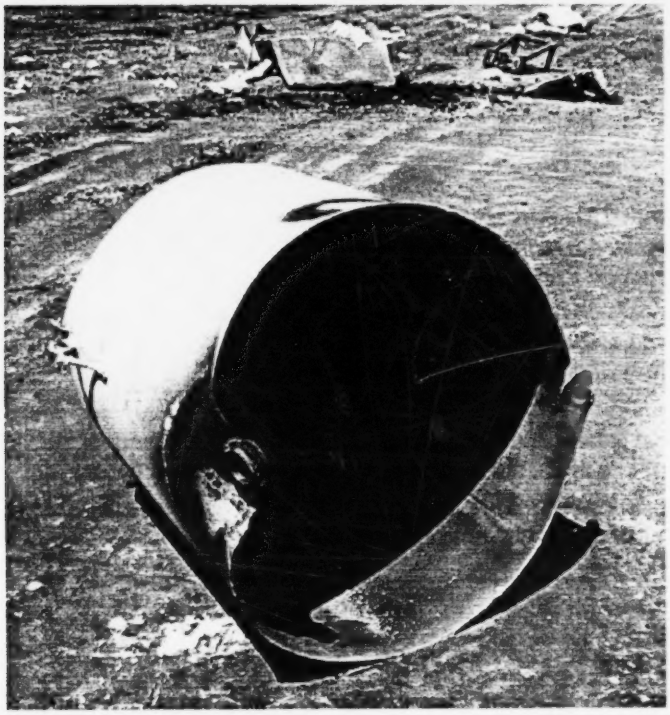

Figure 16: Tub Rocket of Test 02-2 (Flattened Part in Background)

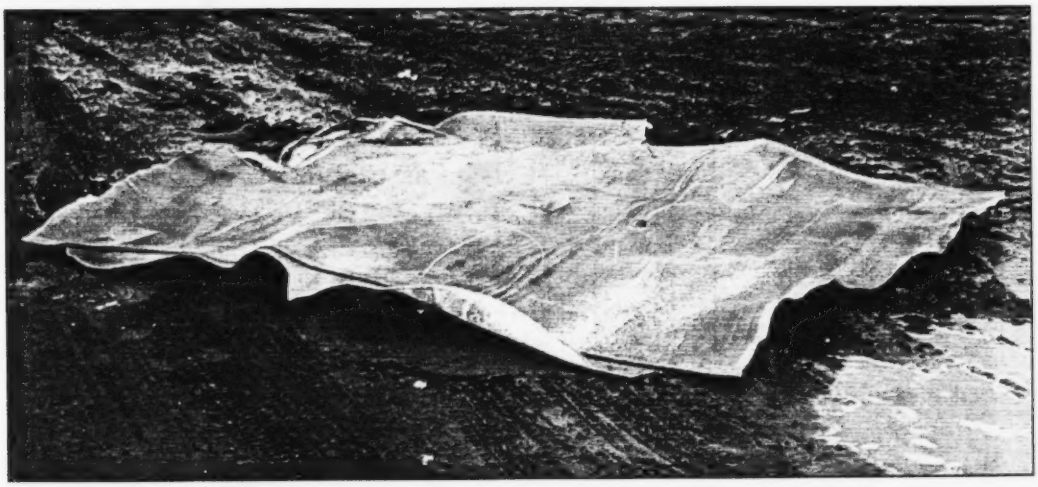

Figure 17: Flattened Tank of Test 02-1 (Missing End Caps)

	Test 00-1: Baseline	Test 00-2: Reduced Blowdown	Test 00-3: Reduced Heating
Fire Conditions	12 Burners on Liquid 2 Burners on Vapour	12 Burners on Liquid 2 Burners on Vapour	8 Burners on Liquid 2 Burners on Vapour
PRV Settings	1.90 kPa 20% blowdown	1.90 kPa 5% blowdown	1.90 kPa 20% blowdown
Nozzle	24 mm	24 mm	24 mm
PRV pipe fitting	1.5 inch	1.5 inch	1.5 inch
Initial Fill	80%	80%	80%
Approximate Volume	1420 L	1470 L	1470 L
Fuel Pressure	40 psi	40 psi	40 psi
Wall Thickness	7.7 mm	7.7 mm	7.7 mm
Initial Temperature	19°C	10°C	17°C
Wind Conditions			> 6 m/s
Time to Failure	783 s 13.0 min	812 s 13.5 min	1032 s 17.2 min
PRV Pops	16	91	28
Fill at Failure	14%	20%	17%
Time to first PRV pop	132 s	141 s	121 s
Time to Destratify	175 s	300 s	245 s
Peak Energy	39,900 kJ	40,100 kJ	37,600 kJ
Wall Temp at 5 minutes	576°C	581°C	491°C
Wall Temp at Failure	810°C	790°C	780°C
Time to 427°C Wall Temp	196 s	186 s	241 s
Type of Failure	Large Finite Failure	Small Finite Failure	Large Finite Failure
Initial Jet	Massive Jet	Jet flare	Massive Jet
Fireball	D < 40 m t < 2 s	No	No
Number of pieces	1	1	1
Failure Description/ Projectile Hazards	27 inch long failure. Tank rolled off stand. Moved 5 m.	8.5 inch long failure	21.5 inch long failure
Final Location of Tank	Between Bunker and Pad		
Additional Damage	None	None	None

Table 7: Summary of 2000 Tests

	Test 01-1: Baseline	Test 01-2: Reduced Blowdown	Test 01-3: Baseline Repeated	Test 01-4: Reduced Blowdown Repeated	Test 01-5: Increased Blowdown	Test 01-6: Reduced Heating
Fire Conditions	10 Burners on Liquid 3 Burners on Vapour	10 Burners on Liquid 3 Burners on Vapour	10 Burners on Liquid 3 Burners on Vapour	10 Burners on Liquid 3 Burners on Vapour	10 Burners on Liquid 3 Burners on Vapour	4 Burners on Liquid 3 Burners on Vapour
PRV Settings	1.90 kPa 30% blowdown	1.90 kPa 5% blowdown	1.90 kPa 30% blowdown	1.90 kPa 5% blowdown	1.90 kPa 45% blowdown	1.90 kPa 5% blowdown
Nozzle	21 mm	21 mm	21 mm	21 mm	21 mm	21 mm
PRV pipe fitting	2 inch	2 inch	2 inch	2 inch	1.5 inch	1.5 inch
Initial Fill	80%	80%	80%	80%	80%	80%
Approx Volume	1460 L	1460 L	1460 L	1460 L	1460 L	1460 L
Fuel Pressure	40 psi	40 psi	40 psi	40 psi	40 psi	40 psi
Wall Thickness	7.7 mm	7.7 mm	7.7 mm	7.7 mm	7.7 mm	7.7 mm
Initial Temperature	24°C	13°C	19°C	20°C	20°C	18°C
Wind Conditions	4.2 m/s E	3.3 m/s SW along tank axis	3.3 m/s N	3.6 m/s NW across tank axis	8 km/h NW across tank axis	6 km/h NE along tank axis
Weather	blue sky	cloudy	few white clouds	overcast	blue sky	overcast
Time to Failure	911 s 15.2 min	648 s 10.8 min	938 s 15.6 min	746 s 12.4 min	980 s 16.3 min	601 s 10.0 min
PRV Pops	9	69	11	82	4	38
Fill at Failure	17%	35%	13%	21%	12%	49%
Time to 1st PRV pop	114 s	146 s	140 s	104 s	129 s	215 s
Time to Destratify	180 s	270 s	220 s	210 s	150 s	290 s
Peak Energy	38,100 kJ	40,600 kJ	38,400 kJ	41,400 kJ	34,400 kJ	41,800 kJ
Wall Temp at 5 min	556°C	656°C	625°C	554°C	518°C	738°C
Wall Temp at Failure	710°C	750°C	910°C	700°C	770°C	740°C
Time to 427°C Wall T	201 s	175 s	172 s	141 s	228 s	62 s
Type of Failure	BLEVE	BLEVE	BLEVE	BLEVE	BLEVE	BLEVE
Initial Jet	1.2 s	0.3 s	No	No	No	1.6 s
Fireball	2.4+ s Lifted off screen	4.6 s	2.4 s	No	3.0 s Thin fireball	4.5+ s Lifted off screen
PRV union leak	Big Leak	Small Leak	Small Leak	No	No	No
Number of pieces	1	2	1	1	1	1
Failure Description/ Projectile Hazards	Crack Corkscrewed after PRV fitting 1/3 of tank cylindrical	Corkscrew crack End of tank shot off 40m; N45°W	Crack Corkscrewed after PRV fitting 1/4 of tank cylindrical	Totally Mangled Corkscrew	Flattened except end piece	Flattened
Tank Final Location	Beside PRV wall (inst. Bunker side)	Beside PRV wall (remote Bunker side)	Beside PRV wall (inst. Bunker side)	5 m from pad 5 m from wall	Remained on pad	In front of PRV wall
Additional Damage/ Other Comments	None	Broken Window DA box fell	None	None	None	Broken Window DA box fell

Table 8: Summary of 2001 Tests

	Test 02-1: LBHP	Test 02-2: HBHP	Test 02-3: HBLP	Test 02-4: LBLP
Fire Conditions	4 Burners on Liquid 2 Burners on Vapour	4 Burners on Liquid 2 Burners on Vapour	4 Burners on Liquid 2 Burners on Vapour	4 Burners on Liquid 2 Burners on Vapour
PRV Settings	1.90 kPa 5% blowdown	1.90 kPa 30% blowdown	1.90 kPa 30% blowdown	1.90 kPa 5% blowdown
Nozzle	21 mm	21 mm	21 mm	21 mm
PRV pipe fitting	2 inch	2 inch	2 inch	2 inch
Initial Fill	80%	80%	80%	80%
Approximate Volume	1460 L	1460 L	1460 L	1460 L
Fuel Pressure	40 psi	40 psi	25 psi	25 psi
Wall Thickness	7.1 mm	7.1 mm	7.1 mm	7.1 mm
Initial Temperature	11°C	22°C	22°C	27°C
Wind Conditions	1.4 m/s E	1.2 m/s SE across tank axis	2.5 m/s W	2.0 m/s SW along tank axis
Weather			cloudy	blue skies
Time to Failure	567 s 9.4 min	523 s 8.7 min	651 s 10.8 min	641 s 10.7 min
PRV Pops	29	2	2	29
Fill at Failure	51%	52%	53%	61%
Time to first PRV pop	264 s	250 s	300 s	292 s
Time to Destratify	450 s	250 s	350 s	475 s
Peak Energy	42,100 kJ	38,900 kJ	39,600 kJ	41,000 kJ
Wall Temp at 5 minutes	655°C	688°C	586°C	583°C
Wall Temp at Failure	710°C	760°C	730°C	700°C
Time to 427°C Wall Temp	136 s	133 s	193 s	168 s
Type of Failure	BLEVE	BLEVE	BLEVE	BLEVE
Initial Jet	1.9 s	1.7 s	No	No
Fireball	4.7+ s Lifted off screen	4.1 s Very High	Late 2.0 s after rupture	No
PRV union leak	Yes	Yes	Yes	Yes
Number of pieces	3	3	3	3
Failure Description/ Projectile Hazards	Flattened Two End Caps	Tub Rocket Buckled tank stand	Flattened Small Rocket	Tub Rocket
Final Location of Tank		Beyond PRV wall (on Road)	On Pad	By PRV Wall
Additional Damage/ Other Comments	Broken Windows Burner thru Roof	Tremendous Impact w/ Wall	High Thermal Radiation near	

Table 9: Summary of 2002 Tests

4.2 Wall Temperature

The vapour space wall temperatures under the burners are of interest because they are an indication of the tank's weakened state prior to thermal rupture. As mentioned in the previous chapter, four thermocouples were used to measure the wall temperature directly under the burners. Some of the thermocouples were centred under the burners, while some were between burners.

4.2.1 Raw Wall Temperature Data

Figure 18 shows the raw temperature data from Test 01-4. Notice that there is a difference of up to 80°C between the highest and lowest indicated temperature. Also, the only thermocouple that was not directly below a burner did not give the lowest reading. In order to compare wall temperature data for the various tests, an arithmetic average temperature was used.

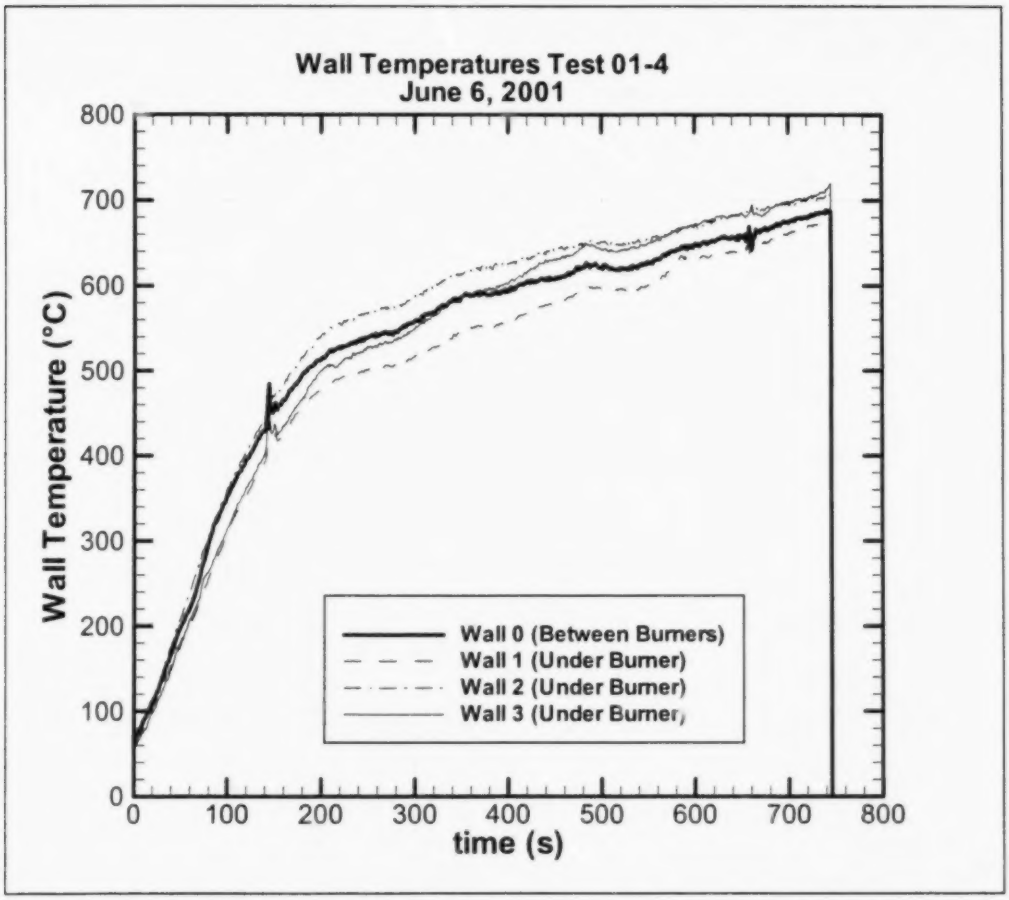

Figure 18: Wall Temperature from Test 01-4

In several of the tests, just before failure, the thermocouples were separated from the tank wall when the plastic deformation and bulging became large. Figure 19 shows the indicated average wall temperature for Test 01-3. Note that there is a temperature rise at approximately 900 seconds which results from the detached thermocouples as a result of the bulging wall. The indicated wall temperatures were adjusted to remove this sudden temperature rise by extrapolating the data from before the bulge. Figure 20 shows the adjusted average temperature plots for a variety of tests.

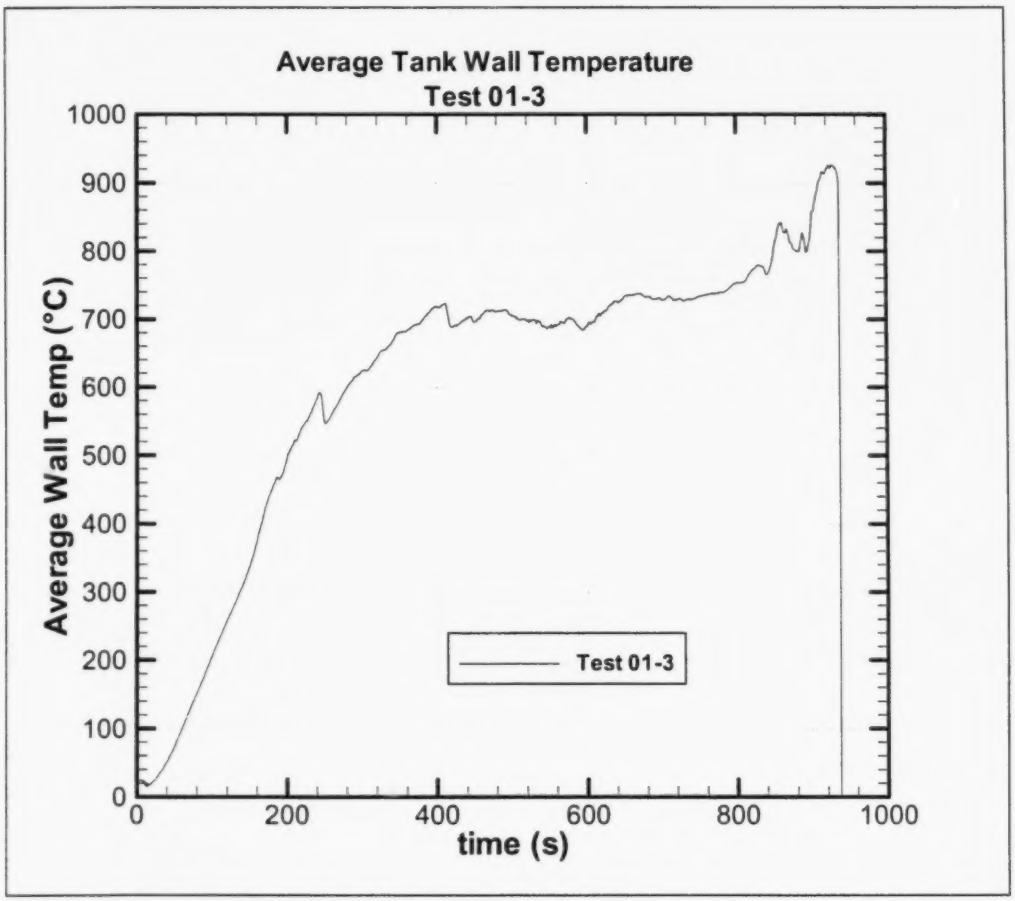

Figure 19: Test 01-3 Wall Temperature Showing Effect of Bulging Wall

4.2.2 Repeatable Wall Temperatures

Figure 20 shows the average wall temperatures for a number of tests. Notice how the temperature rise is steep at first and in most cases reaches a steady state where stabilization occurs. The temperature rise from test to test differs in Figure 20 because the fire conditions were different from test to test.

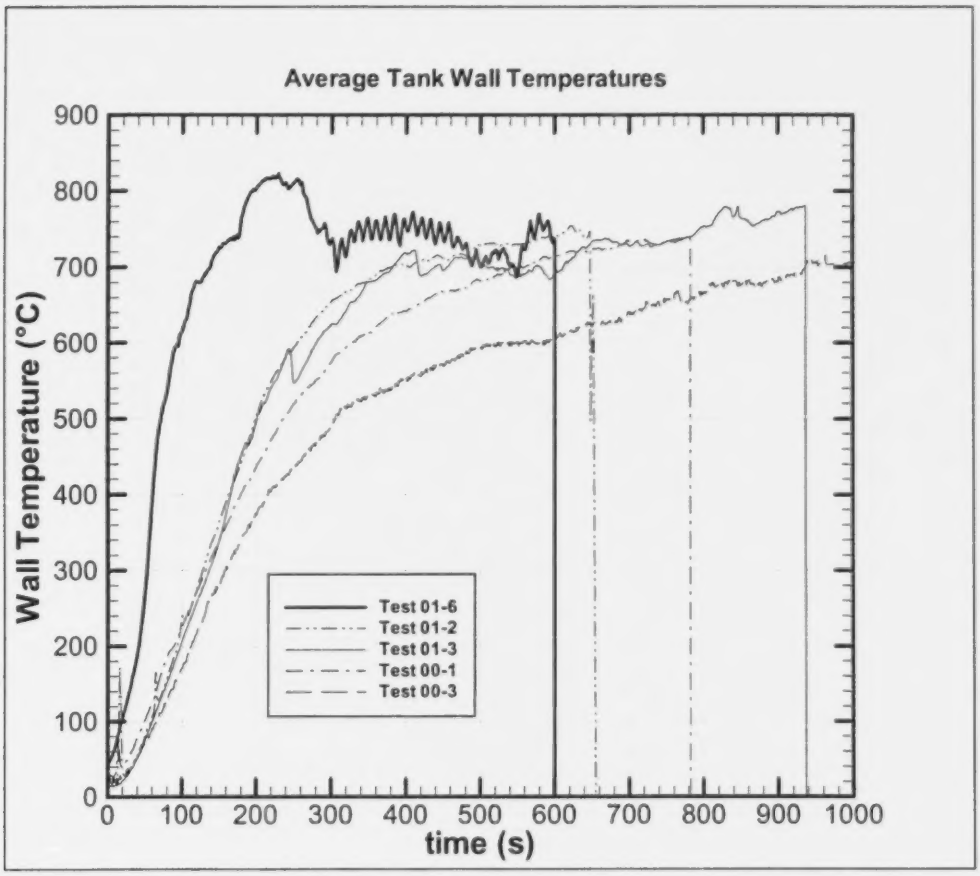

Figure 20: Wall Temperatures for Various Tests

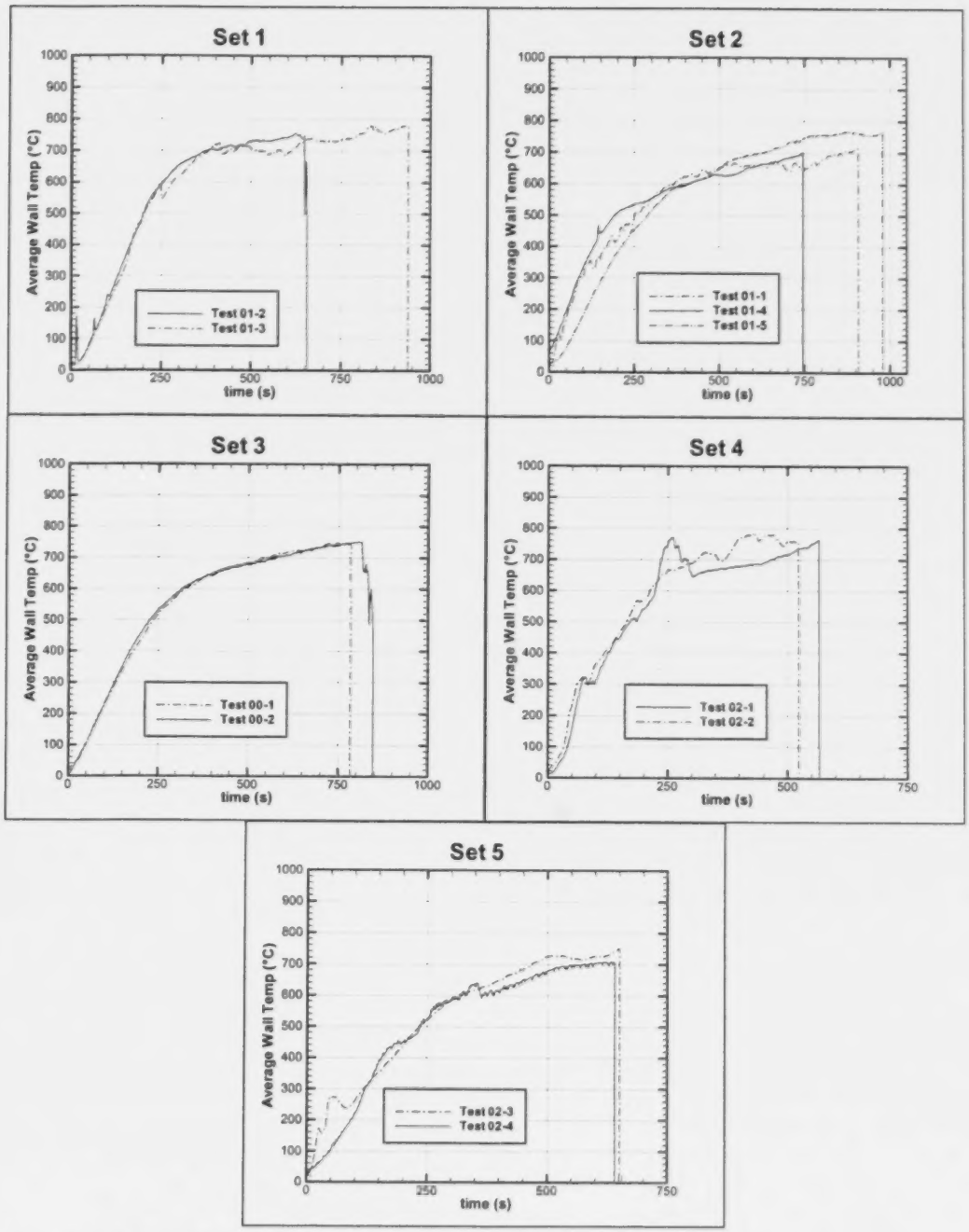

Figure 21: Comparison of Tank Temperatures for Similar Fire Conditions

		Blowdown	Vapour Burners	Liquid Burners	Fuel Pres (psi)
Set 1	Test 01-2	5%	3	10	40
	Test 01-3	30%	3	10	40
Set 2	Test 01-4	5%	3	10	40
	Test 01-1	30%	3	10	40
	Test 01-5	45%	3	10	40
Set 3	Test 00-2	5%	2	12	40
	Test 00-1	20%	2	12	40
Set 4	Test 02-1	5%	2	4	40
	Test 02-2	30%	2	4	40
Set 5	Test 02-4	5%	2	4	25
	Test 02-3	30%	2	4	25

Table 10: Input Parameters for Each Set

The high momentum propane burners were used to heat the tank wall because of their repeatable behaviour and minimum influence from wind. Figure 21 shows the vapour space wall temperature for matching tests. Each set shown in Figure 21 had identical fire conditions. The number of burners in each set was constant and the wind conditions were similar. Notice that the temperature curves are very similar within each set. It is important to always compare tests with similar fire conditions. Table 10 shows the input parameters for each set shown in Figure 21.

4.2.3 Wall Temperature Discussion

4.2.3.1 Liquid Space Burner Location

Test 01-6 and Test 00-3 are the only two tests that do not have a matching test. These two tests are shown in Figure 20. Notice that the wall temperature in Test 01-6 was significantly higher than all other tests despite fewer liquid space burners, while Test 00-3 had lower wall temperatures with fewer liquid space burners. The big difference was that Test 01-6 had the mid-section burners removed, while Test 00-3 had the bottom burners removed.

It is clear from the above observation that the location of liquid space burners influences fluid motion and liquid swell which influences vapour space wall temperatures. It is hypothesized that the removal of the burners nearest the liquid/vapour interface, as was done in Test 01-6, reduces the swelling rise and splashing of the liquid and allows the tank walls to get hotter than if there was mid-section burners.

This suggests that fire location on the liquid wetted wall plays a role on the unwetted wall temperature even though the wetted wall remains relatively cool.

The first two 2002 tests, which had a similar liquid space fire condition to Test 01-6, also showed high vapour space wall temperatures, as shown in Figure 21.

4.2.3.2 Wind Effects

Liquid propane utility burners were used because of the minimal effect on them by wind. It was possible, however for the wind to still deflect the burner jets and influence the tank wall temperatures. If the wind moved the jets to the side or along the tank axis then the wall thermocouples would read a lower temperature. However, a small deflection in the flame jet would have only a small effect on the true wall temperature. In other words, the wind would move the peak wall temperature a few cm but it probably did not change its magnitude dramatically.

Test 00-3, as mentioned above, had the lowest wall temperatures of all the tests. It also experienced the highest wind speeds (25km/h). Perhaps it had the lowest indicated wall temperatures because of the reduced heat flux due to the wind and not due to the reduced heating on the liquid space.

It is hypothesized that while Test 01-6 probably experienced such high wall temperatures because of the lack of burners at the midsection, Test 00-3 did not have such a low wall temperature because of the location of the liquid space burners. It had the lowest indicated wall temperature because of the wind.

For subsequent tests, the wind was carefully monitored and the test was preformed when the wind was at a minimum.

4.2.3.3 Convective Cooling

In 12 of the 13 tests, internal convective cooling on the tank walls was not significant enough to make a noticeable difference on the tank wall temperatures. Test 01-6 was again the exception. The average wall temperature under the vapour space burners dropped by up to 40°C with each PRV cycle. Convective wall cooling was significant in this test because of the high wall temperatures and the low vapour temperatures due to reduced heating and a small blowdown of 5%. (Small blowdown results in cooler vapour than high blowdown, as will be shown later in Section 4.4.)

It is very curious that one test shows very significant convective cooling while the remaining 12 do not. Test 02-1 and Test 02-2 had similar liquid space fire conditions to Test 01-6 but had different wall temperature behaviour. Reasons for this peculiar wall temperature behaviour in Test 01-6 are still being researched.

4.2.3.4 Fuel Pressure and Heat Input Rate

The power of the burners also influences the wall temperature. The fuel delivery pressure was set using a pressure regulator at the supply tank and thus the actual fuel pressure seen at the burner depended on the number of burners used. (There were over 45 metres of pipe for the propane to travel through.) The fewer burners used, the higher the heat flux from each individual burner.

The wall temperatures seen in Test 02-1 and Test 02-2 (Set 4, Figure 21) were higher than the other sets mostly because of the high fuel pressure and the small number of burners (six burners) used.

Figure 22 shows the effect of the reduced fuel pressure in 2002. As expected, a lower heat input rate results in significantly lower wall temperatures.

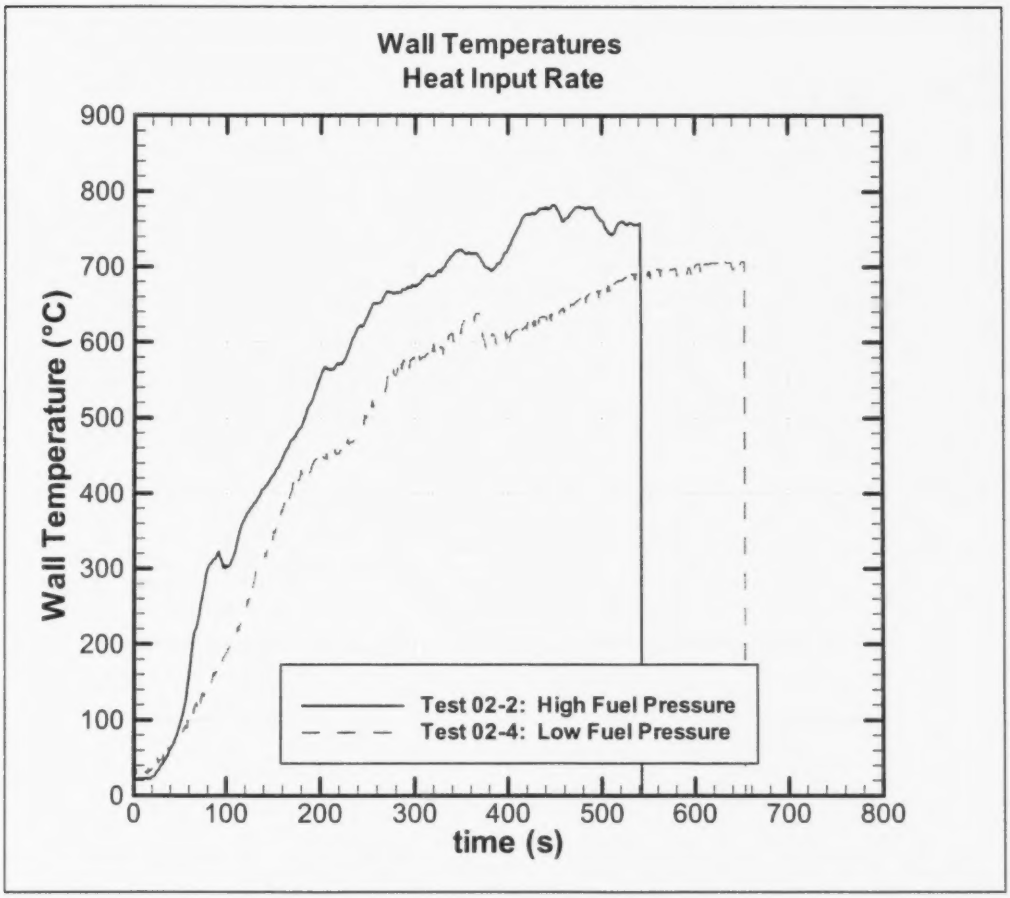

Figure 22: Wall Temperatures for Two Different Heat Input Rates

4.3 Tank Pressure

4.3.1 Tank Pressure Data

Figure 23 shows the measured pressures from Test 01-2 and Test 01-3. This plot shows the typical pressure response for two different blowdowns obtained using the computer controlled PRV. In small blowdown tests, the valve cycled at a high frequency due to the rapid pressure drop to the set tank closing pressure, while large blowdown tests had longer and fewer cycles. As can be seen from the figure, the large blowdown case resulted in a lower average pressure state for the tank and a much later failure time.

Figure 24 shows the tank pressure versus time for Test 01-5, a 45% blowdown test. The pressure plots for the remaining tests can be found in Appendix E.

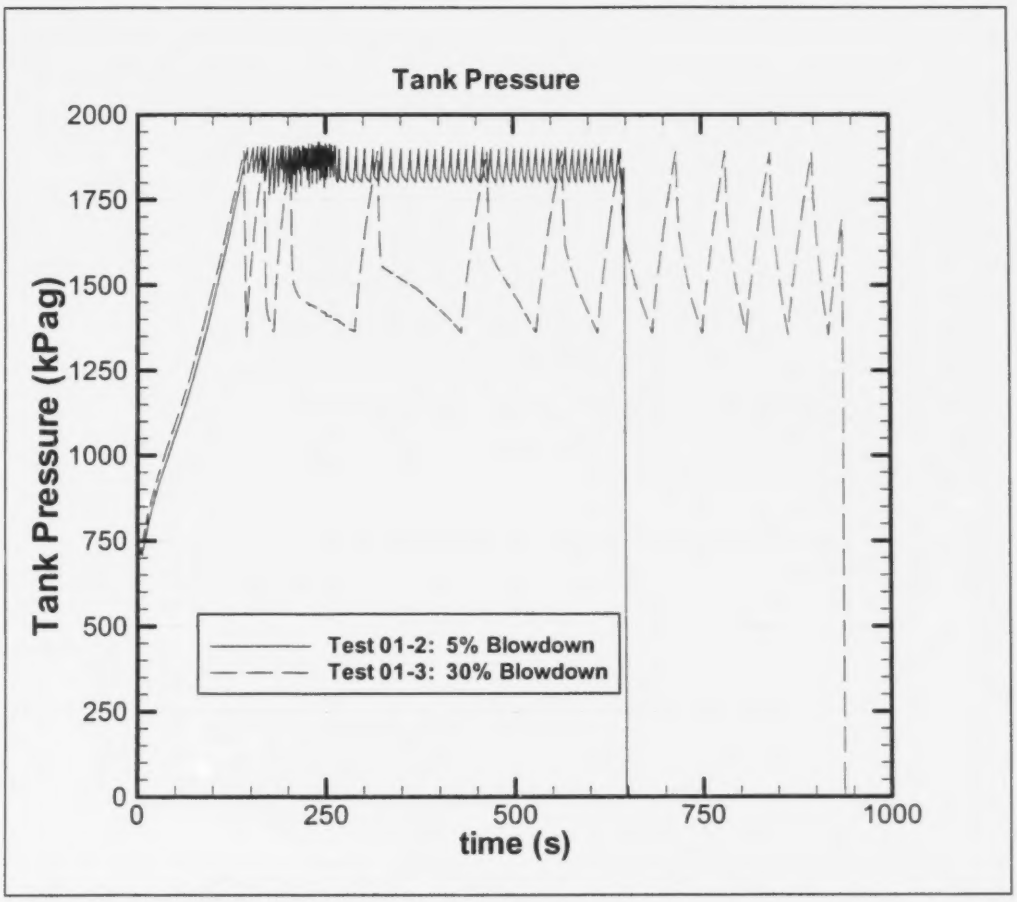

Figure 23: Tank Pressure for 5% and 30% Blowdown

4.3.2 Discussion of Tank Pressure Data

4.3.2.1 Pressure Drop Rate

When the PRV first opens, the vapour space vents initially as if there is no liquid present. However, as the pressure drops, the liquid comes into play. As the liquid generates vapour by flashing, the slope of the pressure curve changes.

In early cycles for the larger blowdown tests, the pressure dropped quickly at first until a certain amount of the vapour was vented and the pressure was low enough for the liquid to start boiling. When the liquid begins to boil, vapour is generated to replace the vented vapour. In order for the pressure to drop down to the PRV closing pressure, boiling had to continue, essentially decreasing the liquid lading temperature, until the corresponding saturation pressure reached the PRV closing pressure. This can be seen clearly in Figure 24. The figure also shows that the pressure drop with time takes a dramatic change in slope. It is expected that the lading will be near isothermal during this second, slower phase of the blowdown, as will be discussed later.

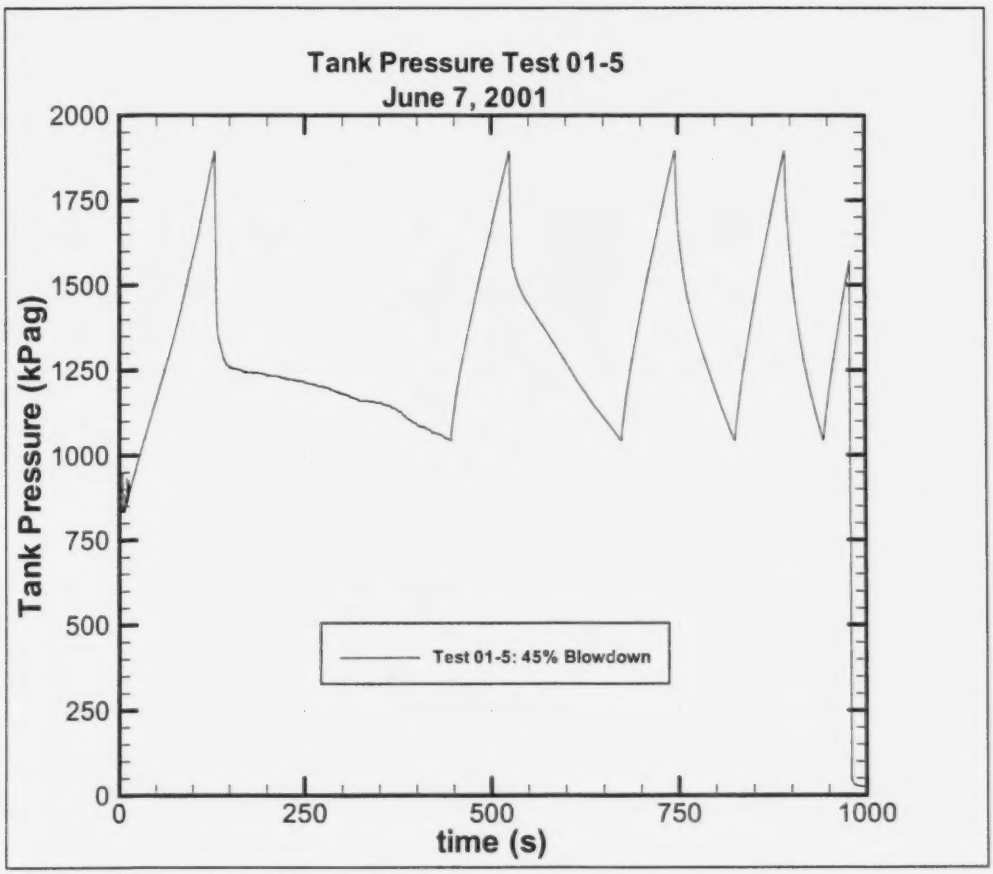

Figure 24: Tank Pressure for 45% Blowdown

In Figure 24, during the second PRV cycle, the slope in the pressure drop changes at a higher pressure than in the first PRV cycle because of a higher liquid lading temperature. The period of a PRV cycle gets smaller as the tank fill gets smaller.

4.3.2.2 Pressure Rise and Location of Fire

The recorded pressure response of the tank was also affected by the fire conditions. The same general pressure behaviour is seen for a wide range of fire conditions. For example, of the first nine tests conducted, eight of them had a very similar initial pressure rise, even though the number of liquid space burners was varied. The ninth test, Test 01-6, however, had a significantly different pressure rise. The difference between Test 01-6 and the previous eight tests was that Test 01-6 did not have any liquid space burners at the mid-section, suggesting that the location of the fire is very important for the pressure rise in the tank.

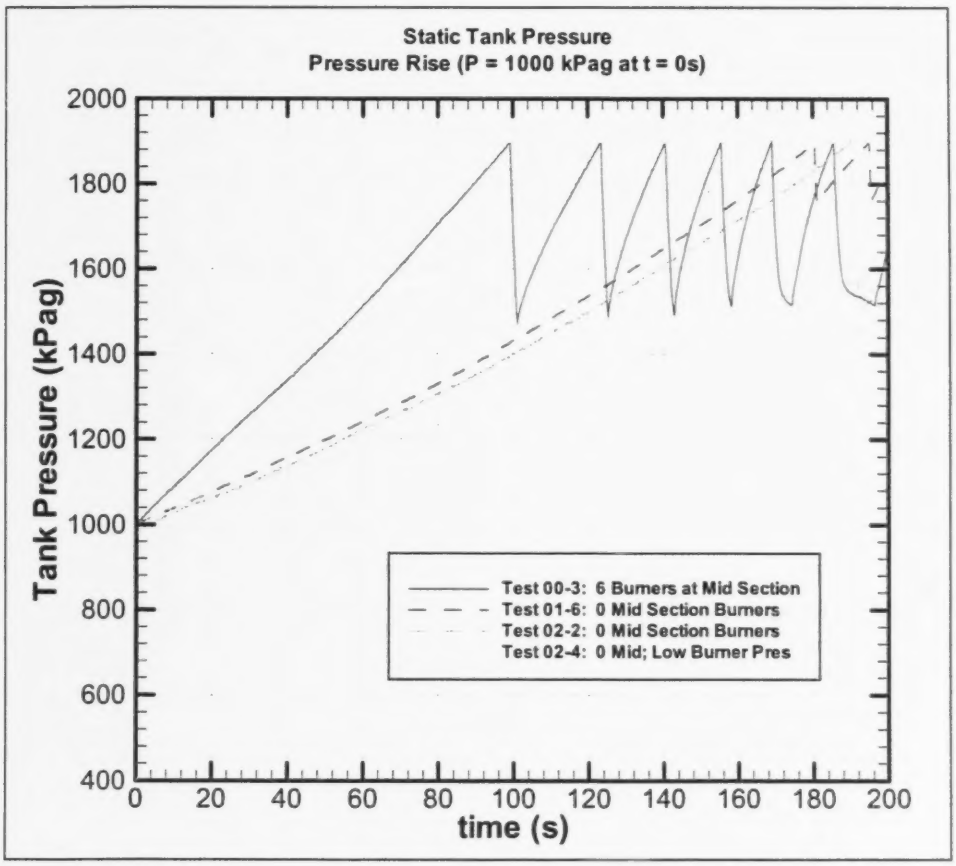

Figure 25: Pressure Rise for Various Fire Conditions

Fire that impinges on the bottom of the tank does not cause the pressure to rise as fast as fire that impinges near the liquid vapour interface. This occurs because much of the heat input at the bottom of the tank goes to heat the large cool propane core. Meanwhile, almost all of the energy transferred from the fire at the interface goes into warming the liquid vapour interface. The fire heat transfer at the liquid vapour interface dominates the initial pressure rise rate. This makes sense, as it is the temperature at the interface that governs the tank pressure.

Test 02-1 and Test 02-2 had a similar pressure rise as Test 01-6 as they all had the same liquid burner set up. In the last two tests in 2002, the pressure rise rate was even slower because of the reduced fuel supply pressure. Figure 25 shows these results. The pressure rise rates for the first eight tests are very similar to the Test 00-3 curve in Figure 25.

4.4 Lading Temperature

4.4.1 Lading Thermocouple Data

In small blowdown tests, because of the short cycle time, less superheated propane vapour was discharged per cycle. In large blowdown tests, however, the cycles were longer and there was more time for the superheated vapour to be discharged. As a result, the vapour temperature in large blowdown tests dropped significantly with each cycle. Also, because the PRV was closed for a longer period of time in the large blowdown cases, the vapour had more time to reach a higher superheat temperature than it did in the small blowdown tests.

These differences can be clearly seen by comparing a 5% blowdown with a 30% blowdown test in Figure 26 and Figure 27. These plots show the temperature readings from all 16 thermocouples in the centre bundle (Bundle 1). The hottest temperature curve corresponds to the highest thermocouple and the lowest temperature corresponds to the lowest thermocouple. (Refer to Figure 11.)

Also notice in Figure 27 that in early cycles, when the PRV opens, the vapour temperature drops quickly at first until it reaches the saturation temperature for the tank pressure. Once this occurs, the temperature rate of change is significantly decreased. During this slower rate of vapour temperature change, the lading is nearly isothermal, as discussed in the previous section.

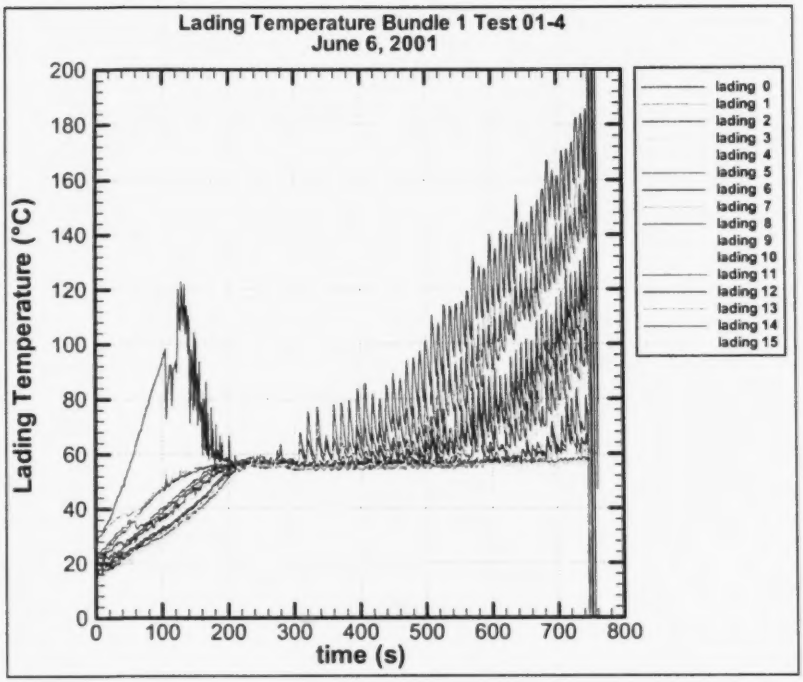

Figure 26: Lading Temperature (5% Blowdown)

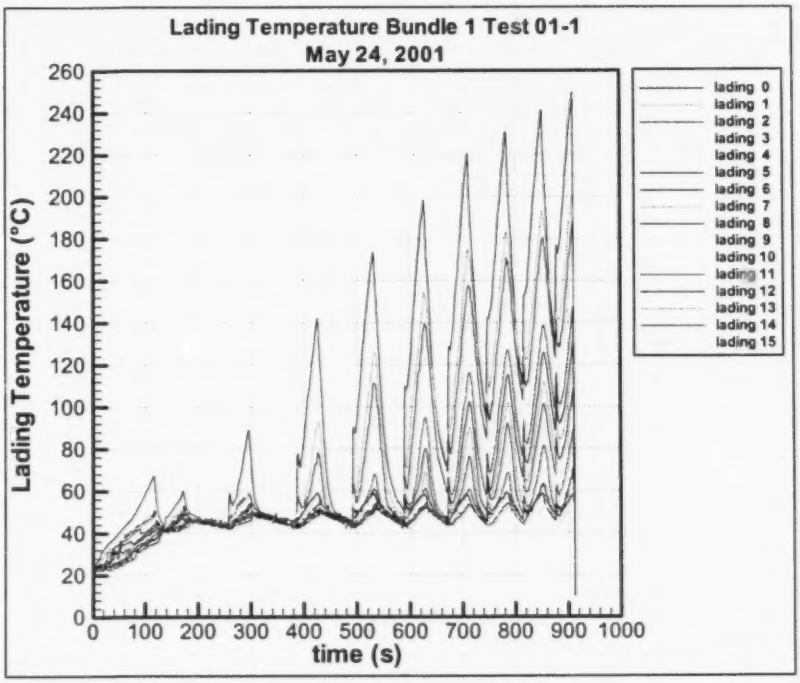

Figure 27: Lading Temperature (30% Blowdown)

Consider the reading of the highest thermocouple (lading 0) before the first PRV pop in Figure 26 and Figure 27. Notice that in the 30% blowdown test the temperature drops significantly because of the longer PRV cycles. Also notice that the peak temperature before PRV operation was about 70°C in Test 01-1 and was about 100°C in Test 01-4. This difference is probably due to small initial differences in thermocouple heights and fill levels and did not affect the vapour space wall temperature, as shown in Figure 21.

4.4.2 Average Lading Temperatures

In order to observe some general trends it is desired to discuss the average liquid and average vapour temperatures. Appendix D gives details on the analysis calculations. Figure 28 shows the average liquid and vapour temperatures for Test 01-1.

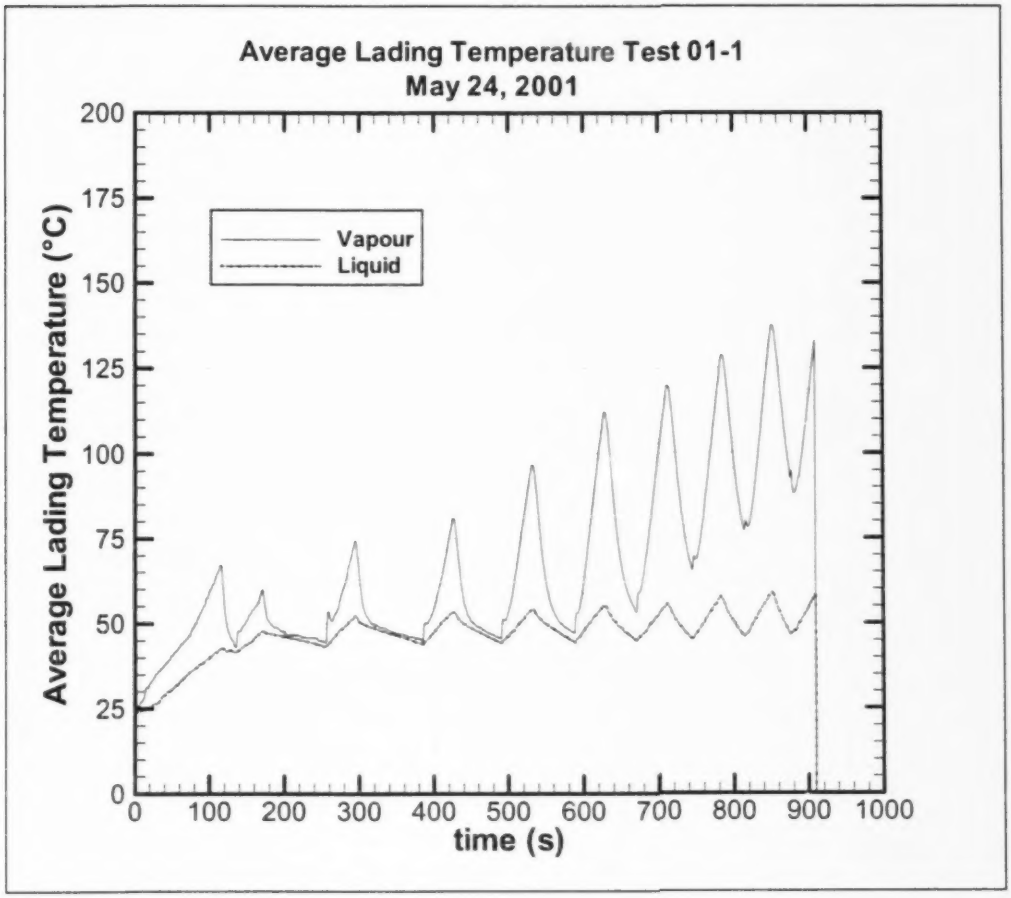

Figure 28: Test 01-1 Average Lading Temperature

4.4.3 Lading Temperature Discussion

4.4.3.1 Average Vapour Temperature

Figure 29 shows the average vapour temperature for various blowdowns. It can be seen that large blowdown tests have lower minimum values and higher maximum values as discussed earlier. In addition, the average vapour temperature is higher for larger blowdown tests. This is undesirable because hotter vapour will provide less convective cooling and could lead to higher wall temperatures.

The hotter vapour temperature can also lead to added spring softening in a real PRV, which is beneficial because a softer spring will tend to reduce the operating tank pressure. This effect was not seen in this test series, of course, because of the computer controlled valve.

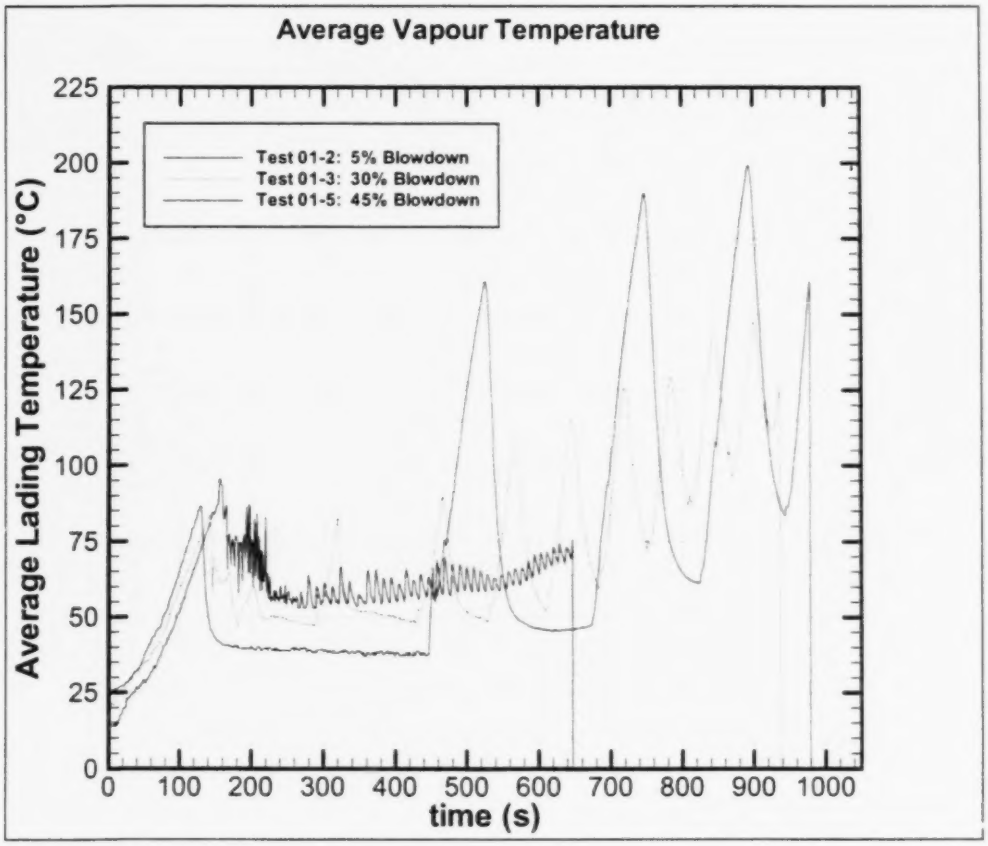

Figure 29: Average Vapour Temperature

4.4.3.2 Average Liquid Temperature

The lower average pressure seen in the large blowdown tests resulted in a lower average saturation temperature and thus a lower average liquid temperature, as shown in Figure 30. This is a very important benefit of large blowdown because it results in significantly reduced energy in the liquid during much of the cycle, which has a large impact on the outcome of the fire impingement. Birk and Cunningham (1994) showed that higher liquid energy increases the chance of a BLEVE.

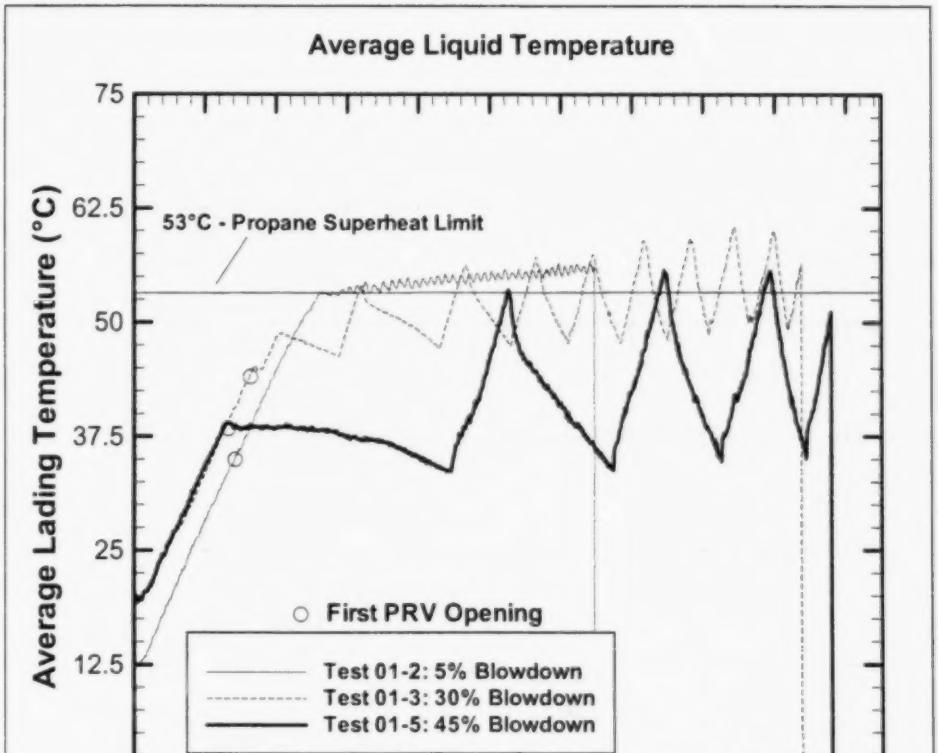

Figure 30: Average Liquid Temperature

Notice how the temperature response to the first PRV pop depends on the blowdown. In the 5% case, the temperature continues to rise after the PRV first opens. This rise continues until the liquid is completely destratified, and the average liquid temperature corresponds to the saturated temperature given the tank pressure.

The reduced heating in the last five tests resulted in lower vapour temperatures. Despite this, in these five reduced heating tests, the average liquid temperature behaves similarly to the average liquid temperatures reported in Figure 30.

Figure 31 shows the tank pressure versus liquid average temperature at failure for all the tests. The atmospheric superheat limit temperature for propane is 53°C and some publications still suggest that this is a critical temperature for a BLEVE to occur. If propane is suddenly depressurized at this temperature it can theoretically be taken all the way down to atmospheric pressure before the superheat limit is achieved. At this point homogeneous nucleation takes place and a significant fraction of the liquid changes phase in a very short period of time and this would give the most powerful phase change explosion. As can be seen from the figure all of the tests were conducted with the liquid temperature very near to the atmospheric superheat limit, but not all failures resulted in a BLEVE.

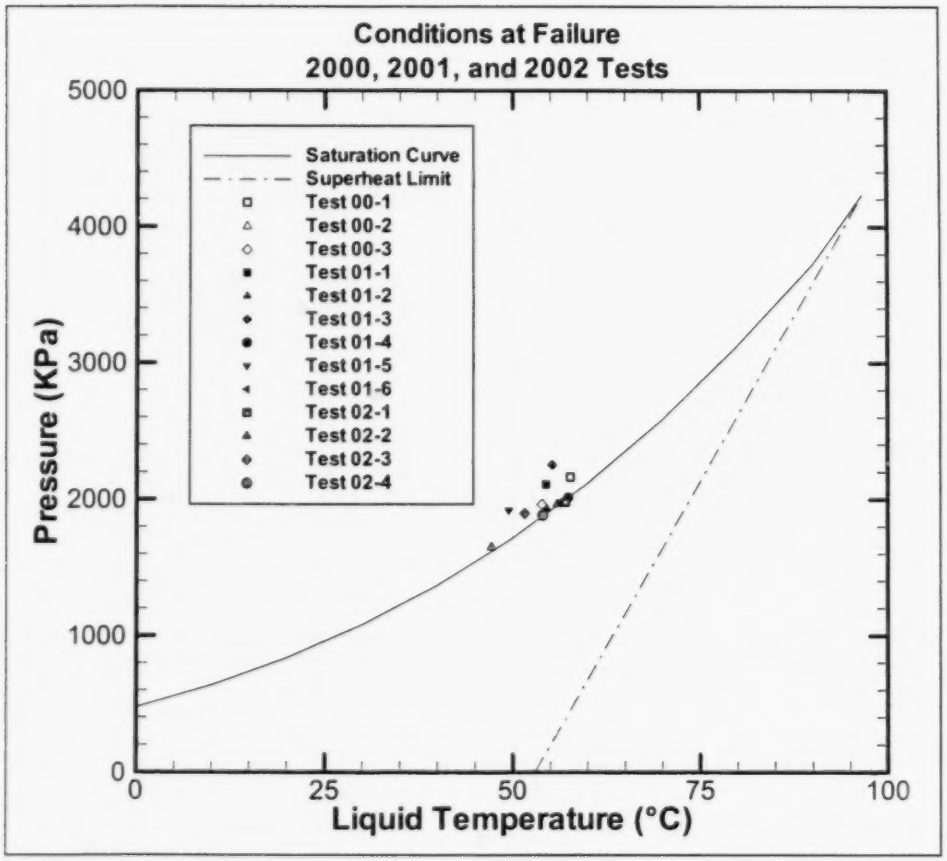

Figure 31: Tank Pressure versus Liquid Temperature at Failure

4.5 Mass Flow Rate

4.5.1 Flow Nozzle Data

The mass flow rate and liquid fill level are very important parameters because the energy stored in the tank and the wall temperatures are heavily dependent on them. Thus, calculating the mass flow through the nozzle correctly requires a certain amount of care. Figure 32 shows sample data from Test 01-3. This is an example of the available data for the mass flow calculation. Notice the rising temperature of the gas leaving through the PRV as test time increases.

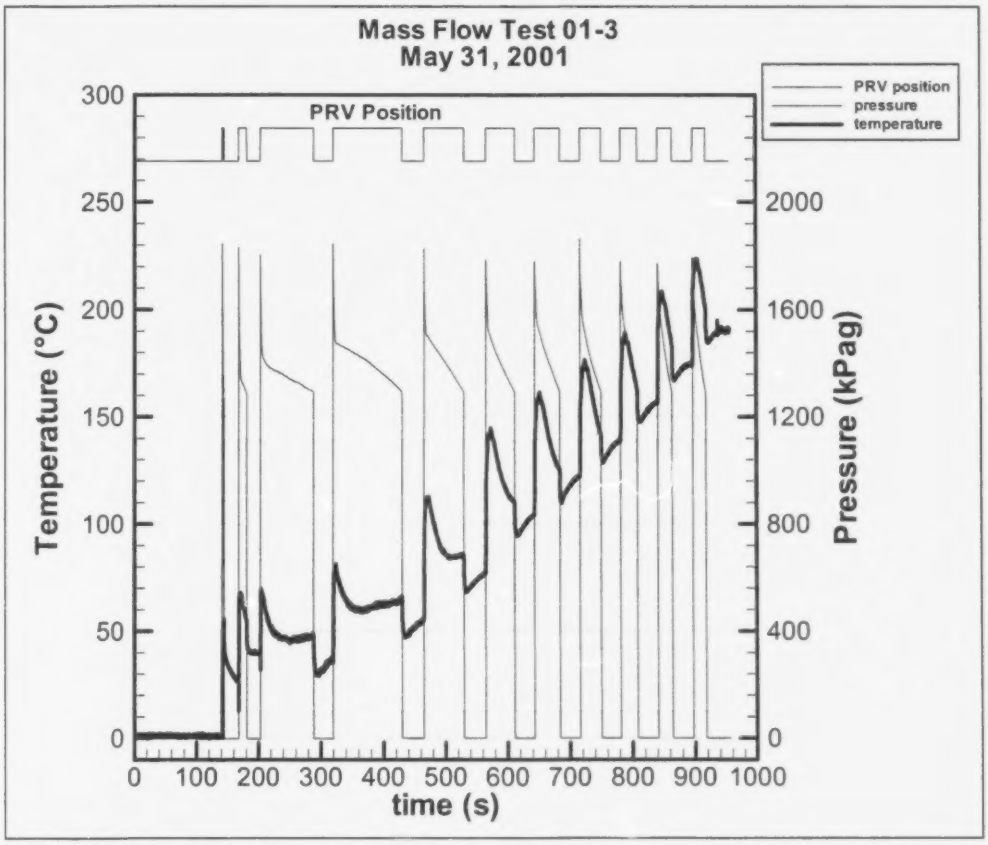

Figure 32: Data from Instrumented Nozzle

4.5.2 Mass Flow Calculations

The mass flow calculations assume a single phase, choked and isentropic flow at the nozzle, and treat the superheated propane vapour as an ideal gas. The methods used were

based on the analysis described by Shapiro. (1954) Appendix D gives the details of the calculations.

4.5.3 Mass Flow Discussion

Figure 33 shows that despite the difference in cycle time, the mass flow out of the tank does not depend on the blowdown. This is expected because the three tests shown in the figure all had the same fire conditions and energy input rate, and thus should have approximately the same energy output rate.

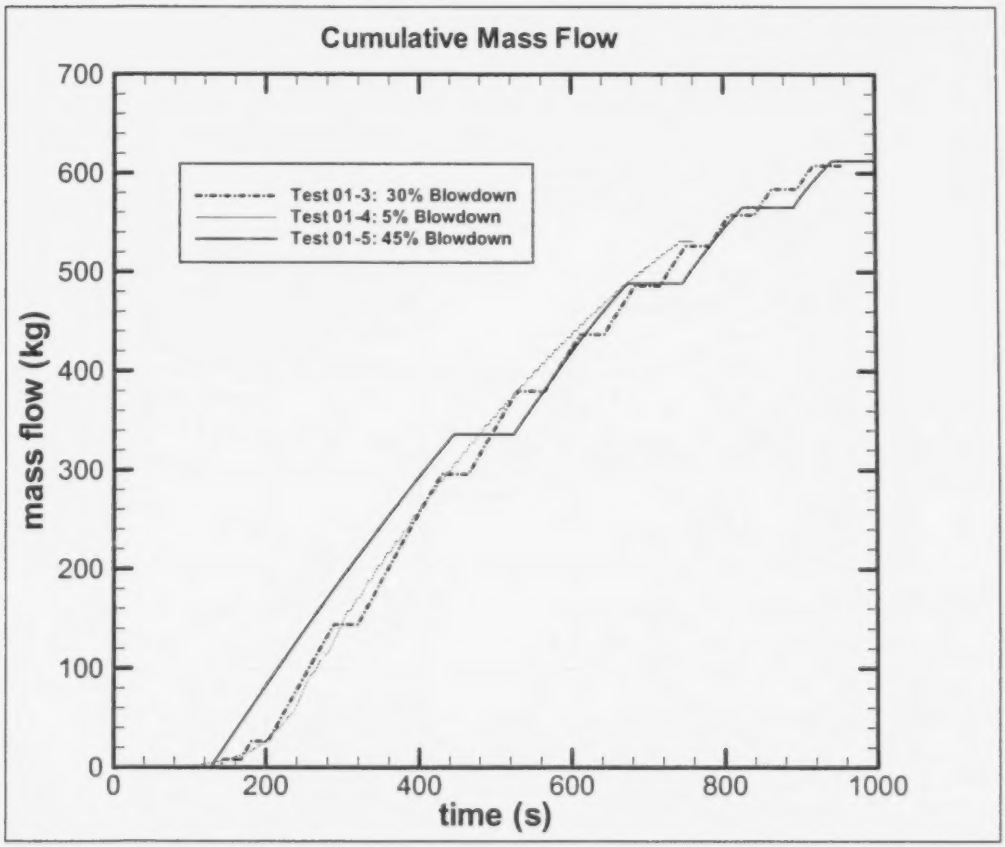

Figure 33: Cumulative Mass Flow for Various Blowdowns

Each tank started with 1460 litres of liquid propane at ambient temperature, corresponding to 730 kg of propane. Using this information and the calculated mass flow rate, the total mass in the tank can be calculated. Figure 34 shows the mass in the tank for a variety of fire conditions. Notice that the flow rate increases as the number of liquid space burners increase. The higher the heat input rate, the faster the tank will empty.

Thus, we can say that the fill level at failure depends on the time of failure and the heat input rate.

The fill is important for several reasons. A large fill means the vapour space is small and this results in a more rapid pressure drop upon initial failure. A very rapid pressure drop will send the liquid into superheat and this will result in a powerful boiling response. Also, a higher fill level means more liquid energy.

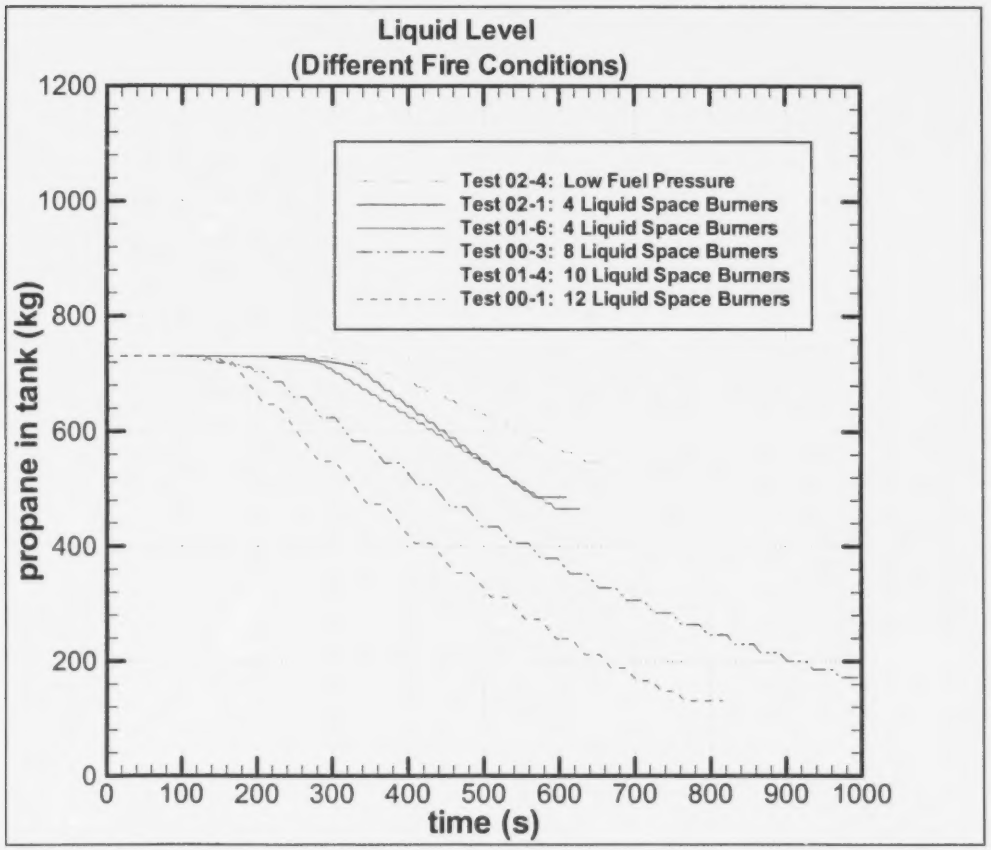

Figure 34: Mass in Tank for Various Fire Conditions

4.6 Tank Energy

4.6.1 Tank Energy Calculations

Next, the isentropic expansion energy stored in each phase was calculated for each time step. The details of these calculations are given in Appendix D.

Figure 35 shows a sample of the results of the calculation for Test 00-1. In this case, the peak energy occurs slightly after the initial opening of the pressure relief valve. After peak energy is obtained, the liquid energy and total energy start to decrease, but the vapour energy continues to increase due to the increasing volume of the vapour space. The vapour energy was approximately equal to the liquid energy at the time of failure.

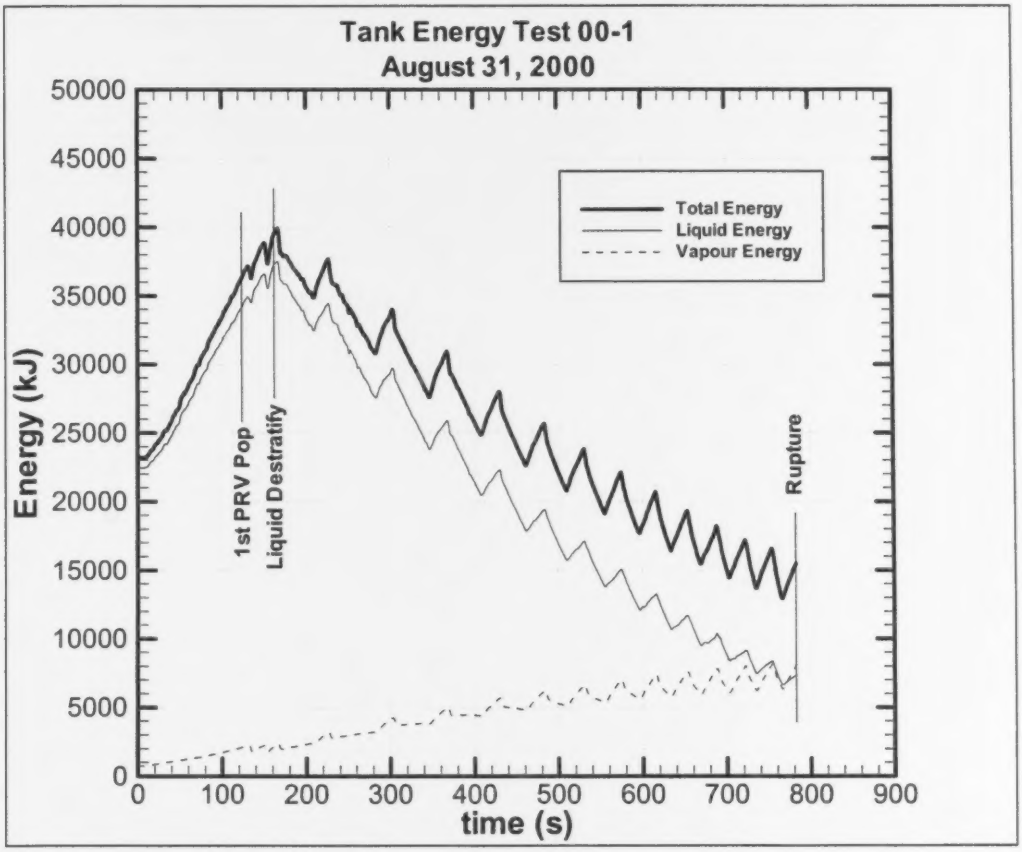

Figure 35: Tank Energy in Test 00-1

Figure 35 also demonstrates that for the duration of much of the test, most of the thermal energy is stored in the liquid. There is more thermal energy stored in vapour if you consider a per-mass-basis, but in a fixed volume situation, the energy stored in liquid is greater. This is why the liquid energy plays such an important role in the hazards and failure process, as shown in the BLEVE Map, in Figure 1.

Figure 36 shows another sample energy plot for Test 02-3. In this case, the peak energy occurs at the same time as the initial opening of the pressure relief valve. Because of the reduced heating and early failure, there is significantly more energy in the liquid phase

than the vapour phase at the time of failure. Figure 37 shows the amount of liquid energy in the tank at failure compared to the amount of vapour energy at failure.

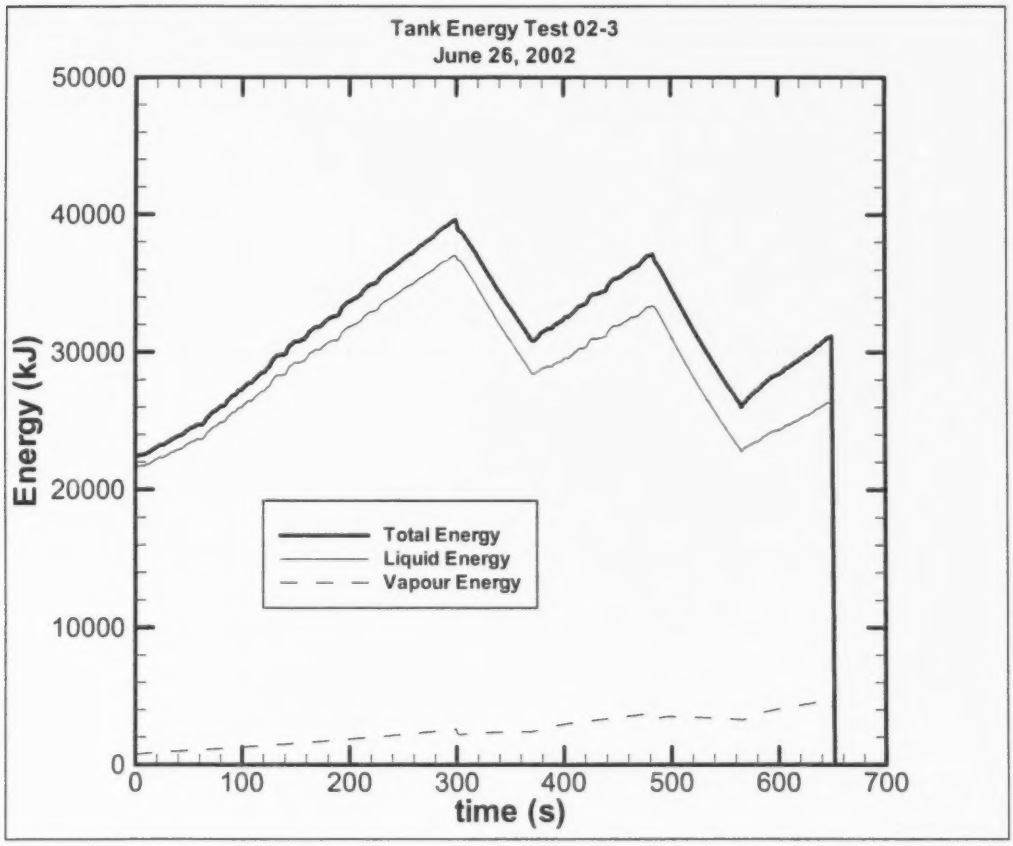

Figure 36: Tank Energy in Test 02-3

4.6.2 Tank Energy Discussion

For tests with the same fire conditions, liquid energy storage is a function of the PRV blowdown. Figure 38 shows that the smaller the blowdown, the higher the peak energy and the later the peak energy occurs. This is related to the time to destratify and will be discussed in the next section.

In the region after peak energy is reached, where the stored energy is decreasing, the rate of energy loss is very similar. In fact, if all of the local peaks are connected for each test, a very similar curve will result. This is consistent with the results in Figure 33 because, for a fixed fire condition, the mass flow out of the tank is independent of blowdown. This means the energy output rate is only a function of the energy input rate. The earlier and lower peak energy associated with the larger blowdown is significant because it is desired to minimize the amount of energy in the tank at the time of failure.

Table 11 also shows how a larger blowdown leads to an earlier and lower peak energy for tests with the same fire conditions (Tests 00-1 and Test 00-2; Test 01-1 through Test 01-5).

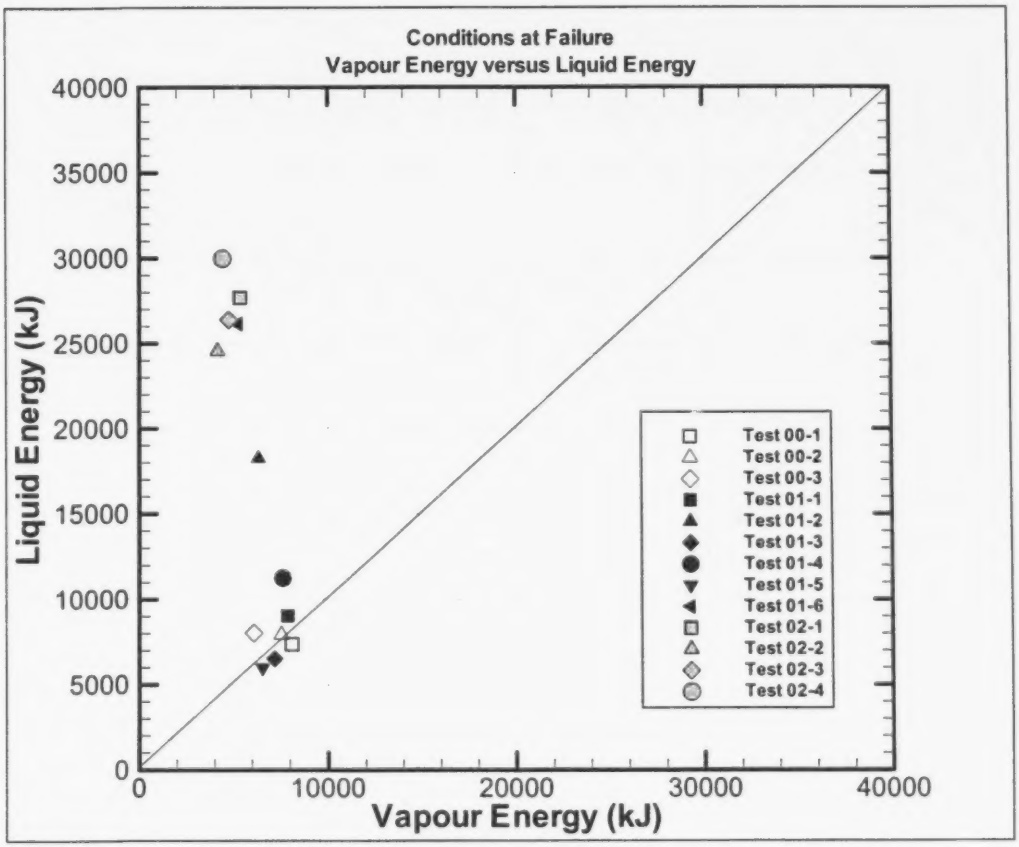

Figure 37: Liquid Energy versus Vapour Energy at Failure

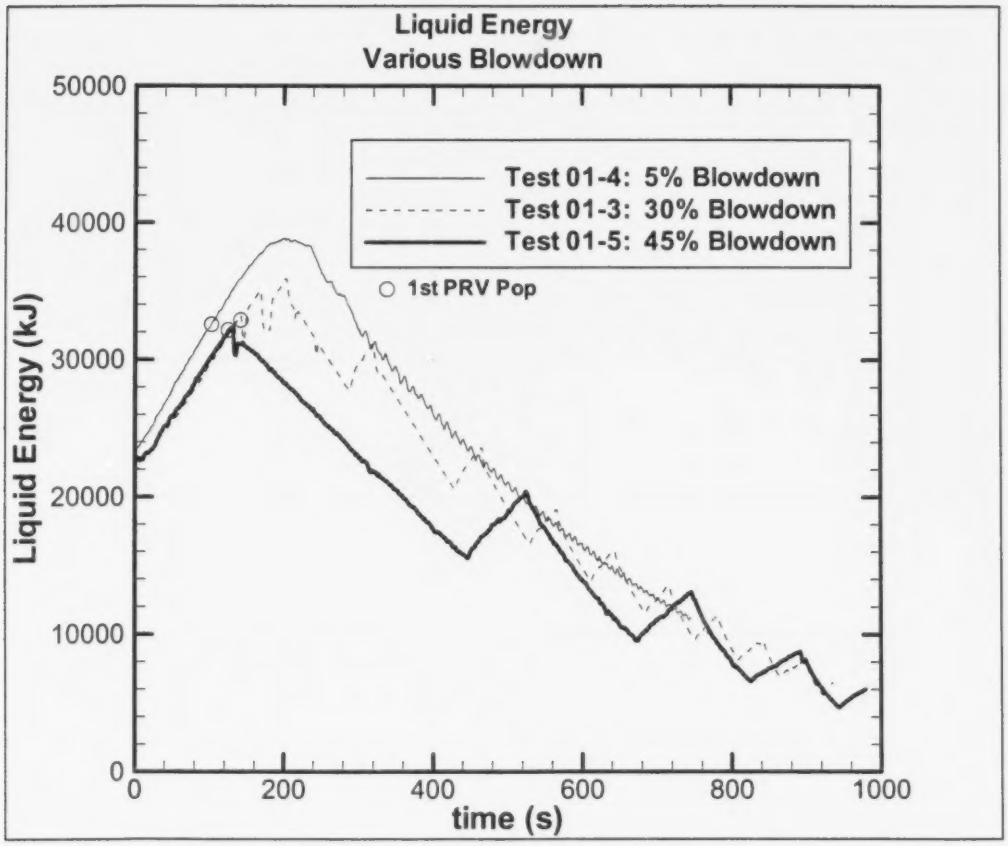

Figure 38: Liquid Energy versus Time for Various Blowdowns

Changing the fire conditions by decreasing the heat input decreases the energy rise rate, delays the peak energy, and reduces the energy decrease rate. Because reduced heating delays the peak energy and reduces the energy decrease rate, it can be more dangerous than full engulfment. If an engulfed tank fails after peak energy is established, which almost always occurs, reduced heating could synchronize liquid peak energy with time to failure, thus giving an even more energetic failure.

	Blowdown (%)	Peak Energy (kJ)	Time to Peak Energy (s)	Time to Destratify (s)
Test 00-1	20	39,900	168	175
Test 00-2	5	40,100	237	245
Test 00-3	20	37,600	231	245
Test 01-1	30	38,100	171	180
Test 01-2	5	40,600	259	270
Test 01-3	30	38,400	201	220
Test 01-4	5	41,400	233	240
Test 01-5	45	34,400	126	150
Test 01-6	5	41,800	286	290
Test 02-1	5	42,100	330	450
Test 02-2	30	38,900	250	250
Test 02-3	30	39,600	300	350
Test 02-4	5	41,000	350	475

Table 11: Peak Energy

4.7 Stratification

Thermal stratification is an important parameter in determining how energy is stored in a pressure vessel. For a fixed fill level and PRV set pressure, the amount of energy stored in a tank can vary greatly depending on the stratification. It was found that the liquid temperature stratification and destratification was a function of both the fire conditions and the PRV blowdown.

4.7.1 Beta Analysis

Stratification is often discussed in terms of a pressure ratio, $\beta=P/P_{sat}$. P is the actual measured tank pressure and P_{sat} is the saturated pressure based on the mass average liquid temperature. If β is equal to 1 the tank is isothermal. A value of β greater than 1 indicates thermal stratification in the tank. The value of β increases as stratification increases. Large stratification is associated with lower energy for a given tank pressure. A higher value of β is therefore beneficial because it is associated with lower energy. If β is less than 1, a superheated or non-equilibrium condition exists. This is usually seen when the tank fails.

When the PRV is closed, the tank pressure increases as long as the tank is engulfed in the fire. Along with increasing pressure comes increasing stratification unless there is a mechanism to dissipate the temperature gradients. When the PRV opens, bulk mixing by bubble motion and phase change works to remove the temperature gradients. The

relative value for β depends on the PRV set pressure and is heavily dependent on scale, so β analyses are only useful when β from similar tests are compared.

	Blowdown	Stratification, β	PRV Open?
Test 00-1	20%	1.079	No
Test 00-2	5%	1.017	No
Test 00-3	20%	1.060	No
Test 01-1	30%	1.125	No
Test 01-2	5%	1.027	No
Test 01-3	30%	1.180	No
Test 01-4	5%	1.011	No
Test 01-5	45%	1.138	No
Test 01-6	5%	1.015	No
Test 02-1	5%	1.000	No
Test 02-2	30%	1.029	No
Test 02-3	30%	1.075	No
Test 02-4	5%	1.015	No

Table 12: Stratification Data at Failure

4.7.2 Stratification Discussion

4.7.2.1 Stratification and PRV Blowdown

Since fluid motion in the tank has a large effect on temperature gradients, the PRV blowdown significantly influences stratification. Figure 39 shows a comparison of beta versus time for three different blowdowns. Tests with small blowdown take a long time to completely destratify after initial PRV opening, while tests with large blowdown destratify very quickly, due to the large drop of pressure and the subsequent boiling.

Another difference seen is that after initial destratification, the tests with large blowdown became stratified to a much higher level when the PRV again closes. If a tank fails very soon after the initial PRV opening, a small blowdown will be beneficial because there is a higher chance that the liquid will be stratified. More likely however, the tank will fail after initial destratification. In this case, a large blowdown is better because there is a chance that failure will occur when the PRV is closed and the liquid has been stratified again. In fact, in this test series, all thirteen tests failed with the PRV closed, as shown in Table 12.

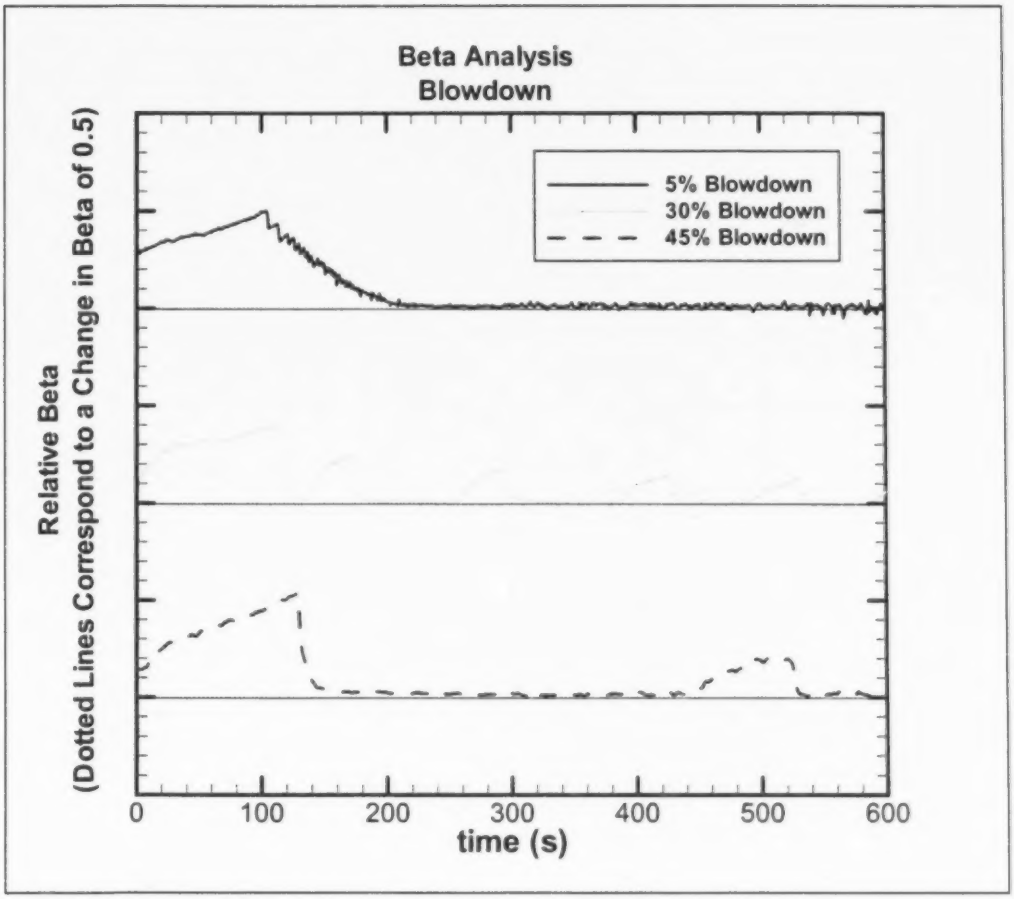

Figure 39: Stratification for Various Blowdowns

4.7.2.2 Stratification and Fire Conditions

Because thermal stratification is essentially a measure of the vertical temperature gradients in the liquid, the location of the liquid space burners also has a very important impact on liquid stratification. Although it is hard to find a general trend between degree of stratification and number of burners, it is clear that the heat distribution is very important.

Figure 40 shows β plotted versus time for Test 00-3 and Test 01-6. Both tests were reduced heating tests, but Test 00-3 used eight burners around the mid-section and tank ends, while Test 01-6 used four burners at the bottom of the tank. Since, in Test 00-3, the energy was applied near the liquid/vapour interface, the hot liquid/vapour interface was even hotter than the liquid at the bottom of the tank. The opposite effect was created in Test 01-6 because no burners were used at the mid-section. Test 01-6 remained stratified for so long because it had a low pressure rise rate and a late PRV opening.

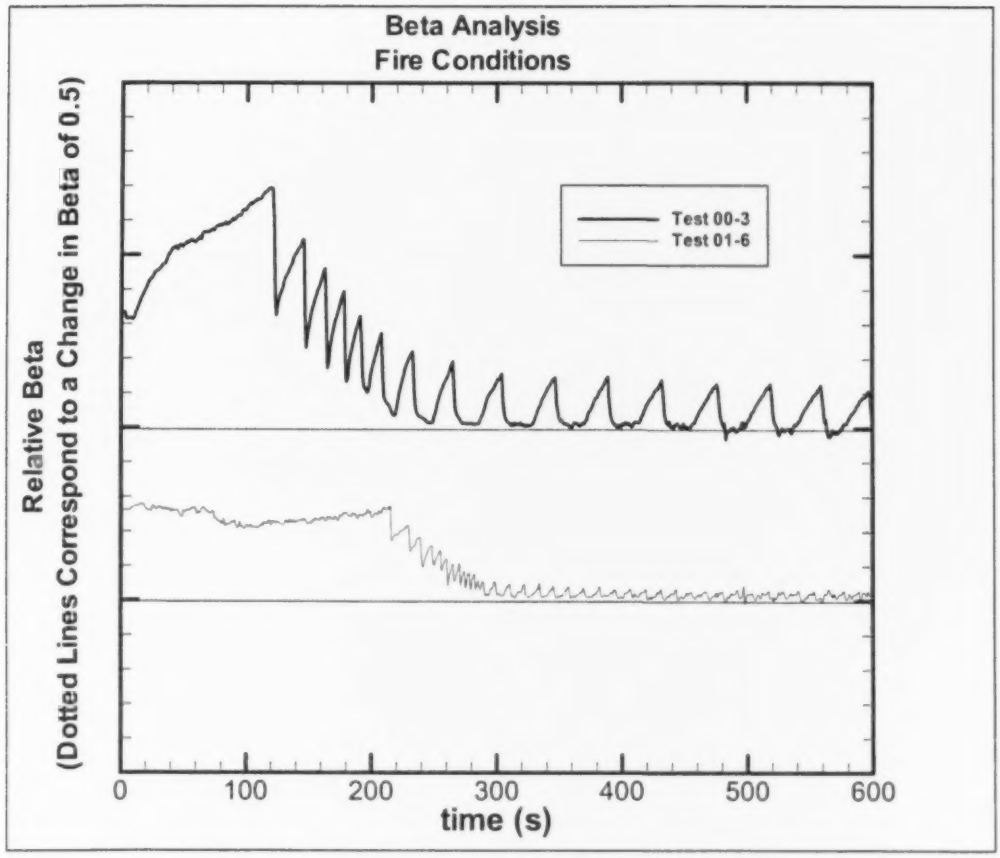

Figure 40: Effect of Burner Location on Stratification

4.7.2.3 Stratification and PRV Behaviour

If a tank is stratified, the average mass flow rate through the PRV is lower than when the liquid is isothermal. When the PRV first opens in a stratified tank, subcooled boiling occurs, in which bubbles are generated at the tank wall. These bubbles rise and collapse into the subcooled liquid core. This results in heat transfer to the liquid and acts to destratify the lading. As a result, a portion of the energy inputted into the tank goes into heating the liquid core.

When the PRV opens on a saturated, isothermal tank, all of the input energy goes into generating vapour. This had been shown experimentally by Birk (1996) and can also be seen in the results presented in Section 4.5 and 4.6. Figure 33 and Figure 34 show that the 5% blowdown tests had a low mass flow rate until the tank destratified. This is seen as a gradual curve before a 'step' curve is established.

It is no coincidence that the erratic pressure behaviour seen early in 5% blowdown tests (Figure 23) stopped at approximately the same time as the tank destratified. After the tank reached isothermal conditions, more vapour was generated, more time was needed to vent the vapour, and thus, the valve could operate at a lower frequency.

Destratification causes the average liquid temperature to rise until it is uniformly heated to the saturation temperature for the tank's PRV set pressure. In the small blowdown tests, where destratification occurs slowly after initial PRV action (see Figure 39), the energy continues to rise after the safety valve first opens. Once the liquid is isothermal at the set pressure, the specific energy in the propane is maximized. The time between initial PRV opening and peak energy is related to blowdown and rate of destratification. This demonstrates that the time to reach the peak liquid energy is closely related to the time for the liquid to destratify. This is also seen in Table 12.

5.0 Additional Discussion

A study of the data collected during the fire tests and the results of the analysis can help one better understand the physics behind propane tanks involved in fire. The results presented in the previous chapter allow for some hypothesizing on why things happen the way they do. This chapter discusses the results and suggests reasons for why the tanks responded to the fire in the way that they did. Appendix F shows a variety of additional analysis plots.

5.1 Tank Failure

5.1.1 Thermal Rupture

In all of the tests, the tanks initially failed by plastic thinning under the vapour space burners as the tank strength decreased. The wall temperature in the severely heated area dictated the tank strength as shown in Figure 41. Figure 42 and Figure 43 show that the wall temperature at failure was in a range between 700 and 800°C, which corresponds to strength between 100 and 60 MPa. This strength is considerably less than the strength of the steel at room temperature (500 MPa).

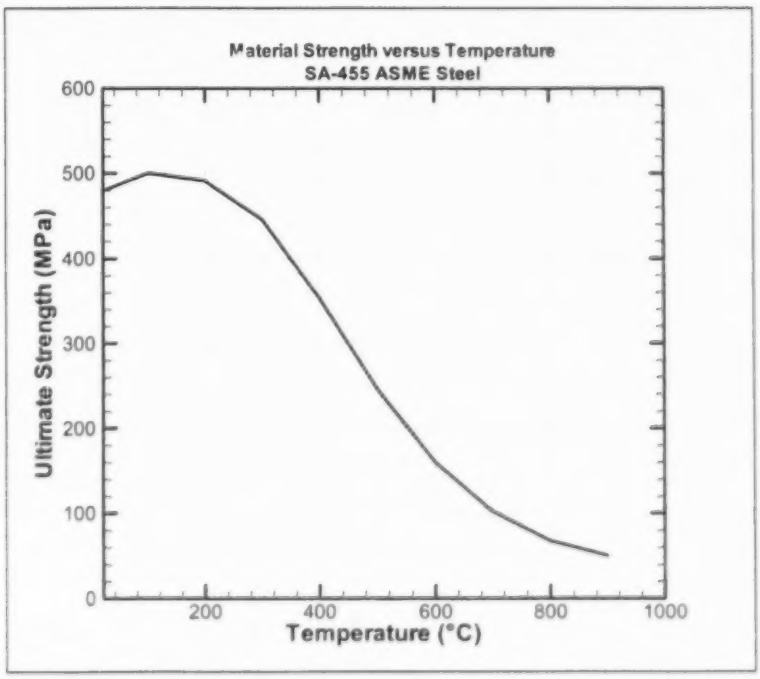

Figure 41: Ultimate Strength versus Temperature for SA-455 Steel

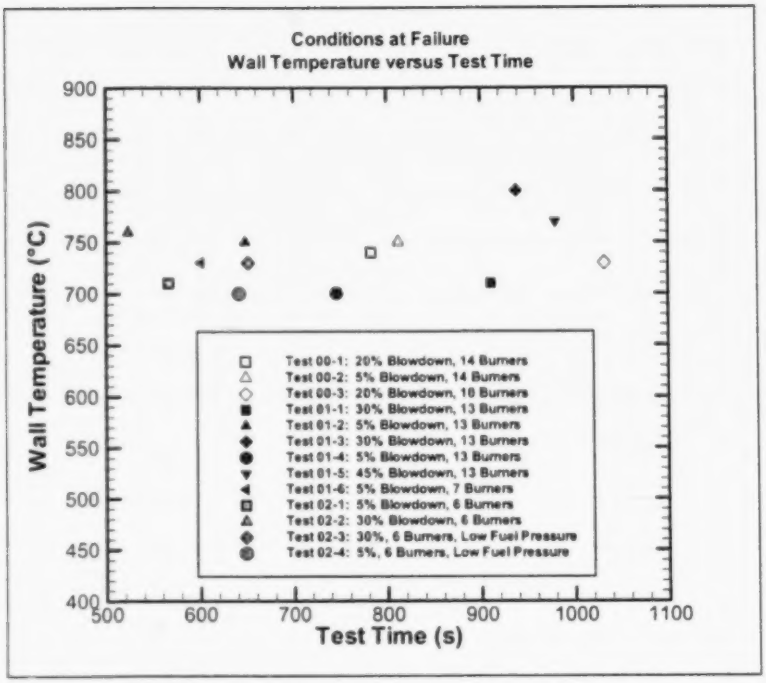

Figure 42: Wall Temperature at Failure versus Test Time

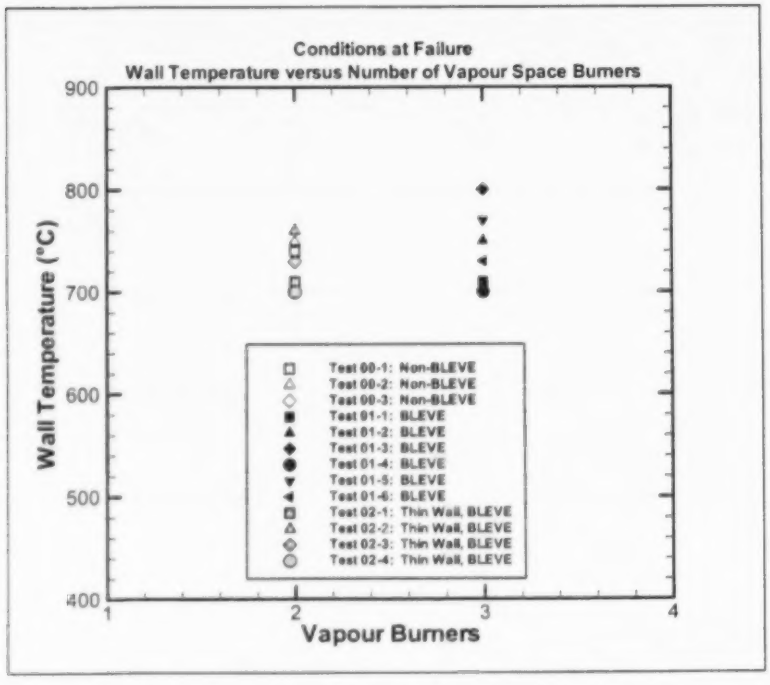

Figure 43: Wall Temperature at Failure versus Number of Burners

The number of vapour space burners did not appear to affect the failure temperature. However, more burners did result in a larger heat affected or weakened area. Because of the larger weakened area, one would expect an earlier failure as vapour space burners are increased. Figure 42 shows that Test 00-2 (two vapour space burners) failed later than similar tests (Test 01-2 and Test 01-4) with three vapour space burners.

When an initial fissure first appears, the crack easily grows through the weakened material. A larger weakened area results in a larger initial crack. It is well documented that once a crack on a vessel grows larger than a certain length the vessel will fail catastrophically. (Baum and Butterfield, 1979)

5.1.2 Failure Analysis

Typically the time to failure for a long cylinder engulfed in fire can be predicted based on the assumption that failure takes place when the hoop stress exceeds the material ultimate strength at the existing wall temperatures. This was not seen in these tests because of the small heated length, as shown in Figure 44.

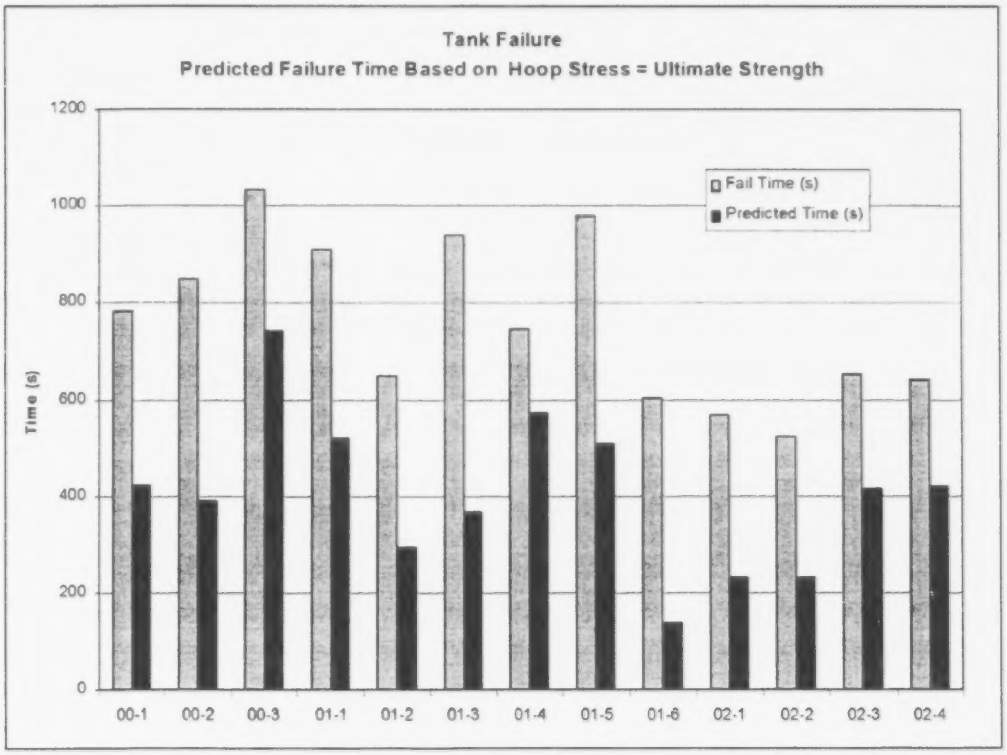

Figure 44: Failure is Underpredicted for all Tests (Assuming Hoop Stress=Tank Strength at Failure)

In all cases the severely heated region was at the tank top over a fraction of one end of the tank, creating a local hot spot. With this kind of heating the hoop stress is partly relieved in the heated spot by the remaining unheated part of the tank, which takes over part of the load.

In these tests, the failure is better predicted by assuming failure occurs when the nominal hoop stress exceeds 150% of material ultimate strength in the heated zone. Figure 45 shows this for Test 01-2. Figure 46 shows both the actual and predicted fail times assuming a failure at 1.5 times the ultimate strength in the weakened area.

Notice in Figure 46 that some tests are still way under predicted. In Test 01-6 for example, the wall temperature increased so rapidly that the failure was predicted much too early using both methods. Figure 47 shows that both failure criteria under predict failure. Figure 47 also shows, however, that the stress at failure was very similar to 1.5 times the ultimate strength in the heated zone at failure. Table 13 shows that the hoop stress is very similar to 1.5 times the ultimate stress at failure for all of the tests.

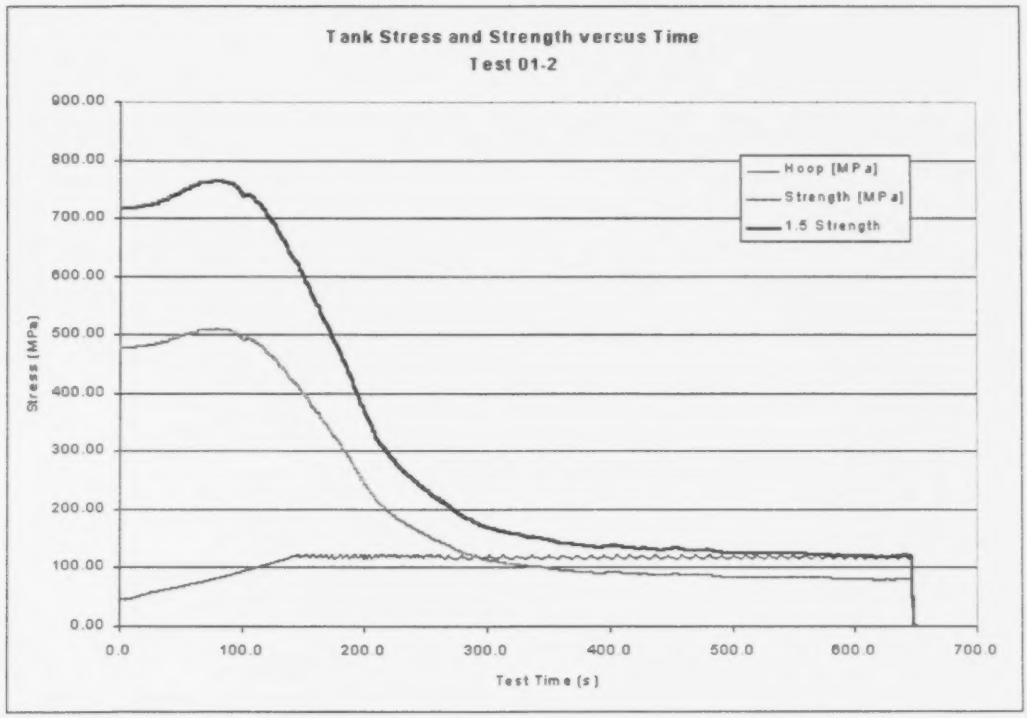

Figure 45: Stress and Strength versus Time for Test 01-2

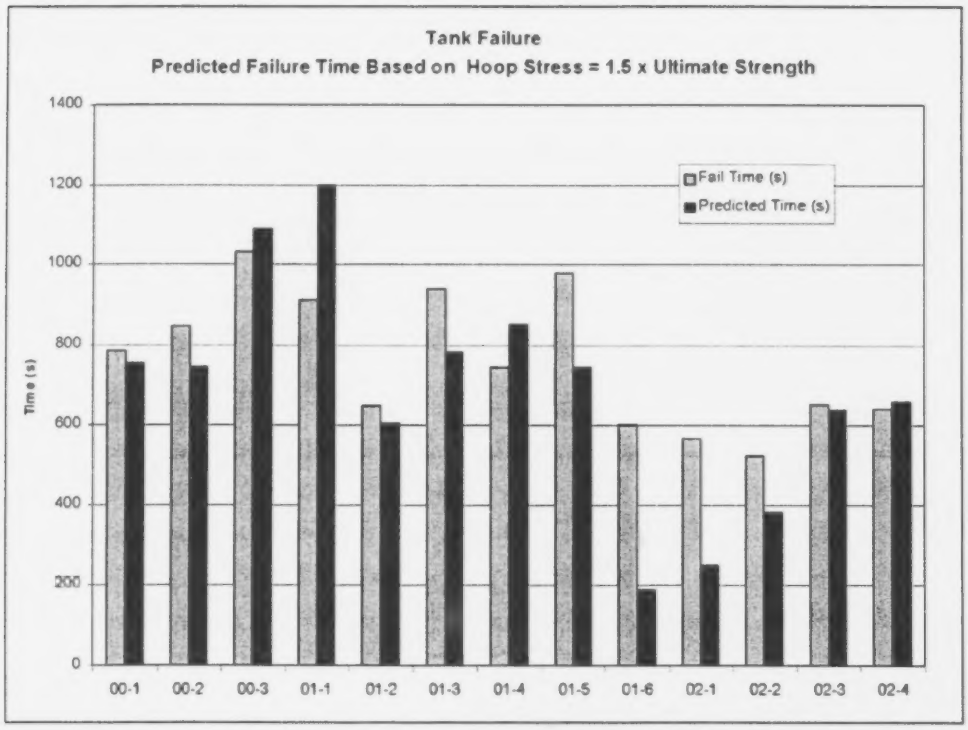

Figure 46: Predicted and Actual Fail Times Assuming Hoop Stress = 1.5 x Ultimate Stress at Failure

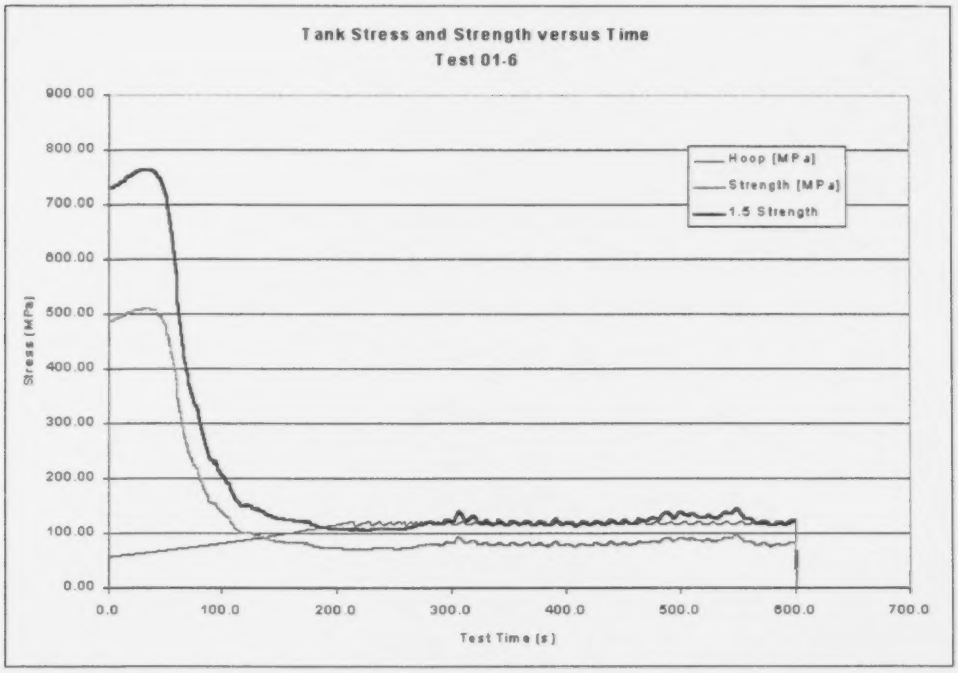

Figure 47: Stress and Strength versus Time for Test 01-6

Test	Hoop/Ultimate at Failure	Hoop/1.5xUltimate at Failure
00-1	1.49	1.00
00-2	1.51	1.00
00-3	1.40	0.94
01-1	1.18	0.79
01-2	1.49	1.00
01-3	1.51	1.00
01-4	1.29	0.86
01-5	1.33	0.89
01-6	1.48	0.99
02-1	1.59	1.06
02-2	1.38	0.92
02-3	1.59	1.06
02-4	1.44	0.96

Table 13: Two Different Failure Criteria

The hoop stress is a good indicator of failure in fire engulfed tanks because the distortion in the tank wall is primarily in the hoop or circumferential direction. However with local heating the distortion is both circumferential and longitudinal. Therefore when a tank is heated locally by a small fire or torch, the failure criteria is likely to change. In this case it is expected that the failure criteria should be based on the Von Mises stress which is calculated from the following for a long cylinder:

$$\sigma_{vm} = \sqrt{\sigma_h^2 - \sigma_h \sigma_l + \sigma_l^2} \tag{5.1}$$

In equation 5.1, h stands for hoop stress and l stands for longitudinal stress. The longitudinal stress is half of the hoop stress, which gives a Von Mises stress in a long cylinder of 0.87 times the hoop stress.

Another factor that should be taken into consideration is that the ultimate strength properties of the steel used in the calculations is always the minimum allowed for the specified grade for steel. In reality the steel ultimate strength is usually 10% or even 20% higher than the minimum.

If we combine these two factors then we could explain that the hoop stress must be in the order of 1.2 to 1.4 times the ultimate strength for failure. Appendix G gives more information on the failure analysis.

5.1.3 Transition between a BLEVE and a non-BLEVE Failure

The 2001 tanks most likely all BLEVEd because the severely heated length was greater than the critical crack length, due to the greater number of vapour space burners. Conversely, the 2000 tanks did not BLEVE because the heat affected area and thus the initial hole size was smaller than the critical crack length. Birk (2002) also discusses this in a paper.

The 2002 tanks BLEVEd with only two vapour space burners. There are two reasons why this occurred:

1. The tanks were approximately 10% thinner in 2002 and the critical crack length decreases for a thinner tank.
2. The tanks failed with more lading energy than the earlier tests and thus there was more energy to propagate the crack. The BLEVE Map in Figure 1 shows how the likelihood of a BLEVE increases as available energy at failure increases.

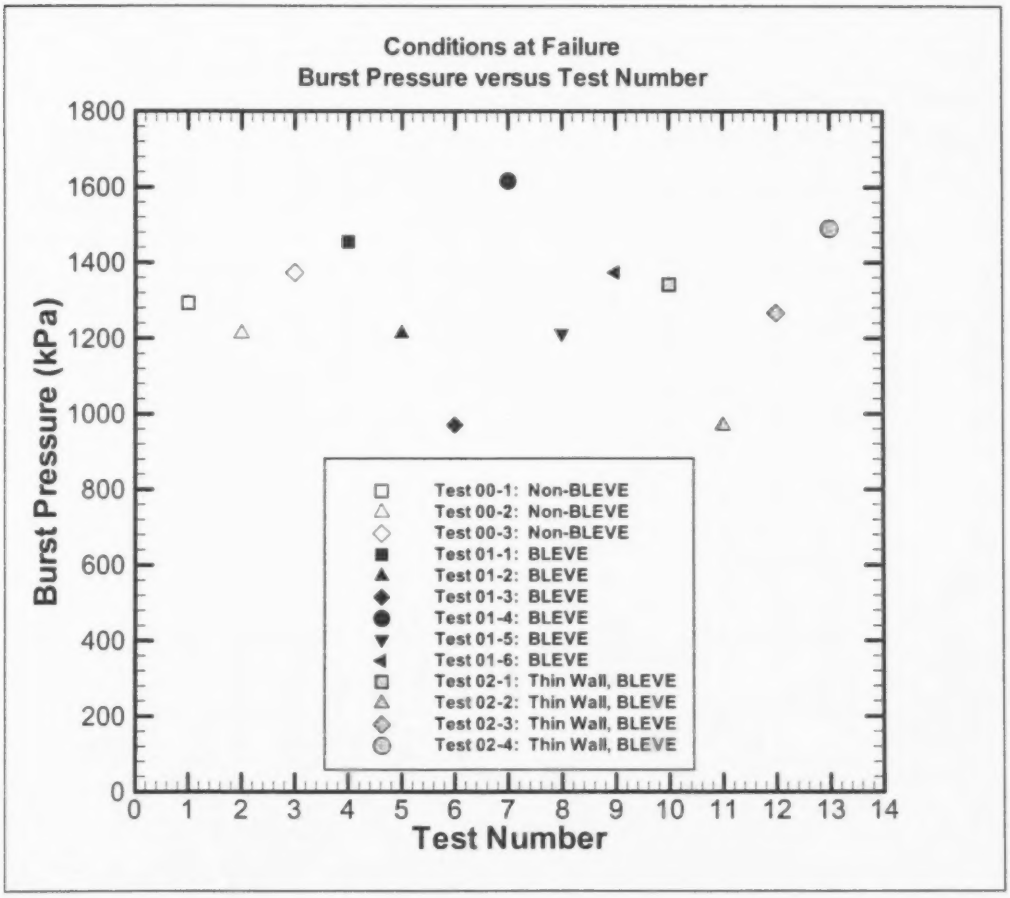

Figure 48: Tank Burst Pressure at Failure

A BLEVE Map (like the one seen in Figure 1) could not be generated for this series of data because of the localized heating in the vapour space. Figure 48 shows that the burst pressure (tank strength) at failure for the 13 tests had no relationship on whether or not the tank BLEVEd.

5.1.4 Critical Heating Length

The BLEVE Map predicted a fire test outcome based on tank strength and liquid energy at failure. It was desired to generate a similar BLEVE map for this test series. This would give us a tool to predict test outcome based on the severely heated length and the liquid energy at failure.

With localized vapour space heating, when the tank wall fails due to thinning, the crack usually grows rapidly through the weak material but it may not grow through the strong surrounding material, unless the pressure transient in the tank is sufficient to keep the crack growing. For the crack to grow the crack tip stress must be above some critical value. (Baum and Butterfield, 1979)

Baum and Butterfield (1979) studied the depressurization of ambient temperature, gas pressurized pipe with machined axial flaws of various lengths. They found that upon rupture, the crack would continue past the ends of the machined flaws to open the full length of the pipe when:

$$\frac{m\sigma_h}{\sigma_f} > 3 \qquad (5.2)$$

where,

$m = (1 + 1.05L^2/(4Rw))^{1/2}$

= Folias bulge parameter

R = pipe radius

w = wall thickness

L = defect length

σ_h = hoop stress remote from defect = PR/w

σ_f = flow stress = $(\sigma_{ult} + \sigma_{yld})/2$

P = internal gage pressure

The stress at the crack tip is $m\sigma_h$ and therefore the above relation suggests the crack tip stress must be three times the flow stress for the crack to propagate into strong material and result in full opening of the pipe.

Recall that the tests of Baum and Butterfield (1979) were for gas pressurized pipe. In our test cases the tanks were pressurized with vapour and saturated liquid. This means the pressure forces caused by the flashing liquid will maintain the crack tip stress for a longer

period of time after initial failure. It is reasonable to assume that the critical value of the crack tip stress would be affected by the presence of the flashing liquid. It is expected that full opening of the pipe or vessel with a flashing liquid will take place at a lower value of the crack tip stress. It is also expected that the critical crack tip stress will be reduced as the liquid energy is increased. Also, with the severe heating it is expected that the stress riser due to bulging will be changed.

Figure 49 shows the crack tip stress ratio $m\sigma_h/\sigma_f$ versus the liquid isentropic expansion energy per unit volume of tank at the time of failure. In this case, the flow stress is for ambient temperature material. The plot includes data from the BLEVE tests of Birk and Cunningham (1997). In all cases the Folias bulge parameter (m) has been calculated using the severely heated length in the tests. We see from this plot that there is no clear dividing line between BLEVE and non-BLEVE. We see that for our tests the critical crack tip stress is $1.5 < m\sigma_h/\sigma_f < 3.5$.

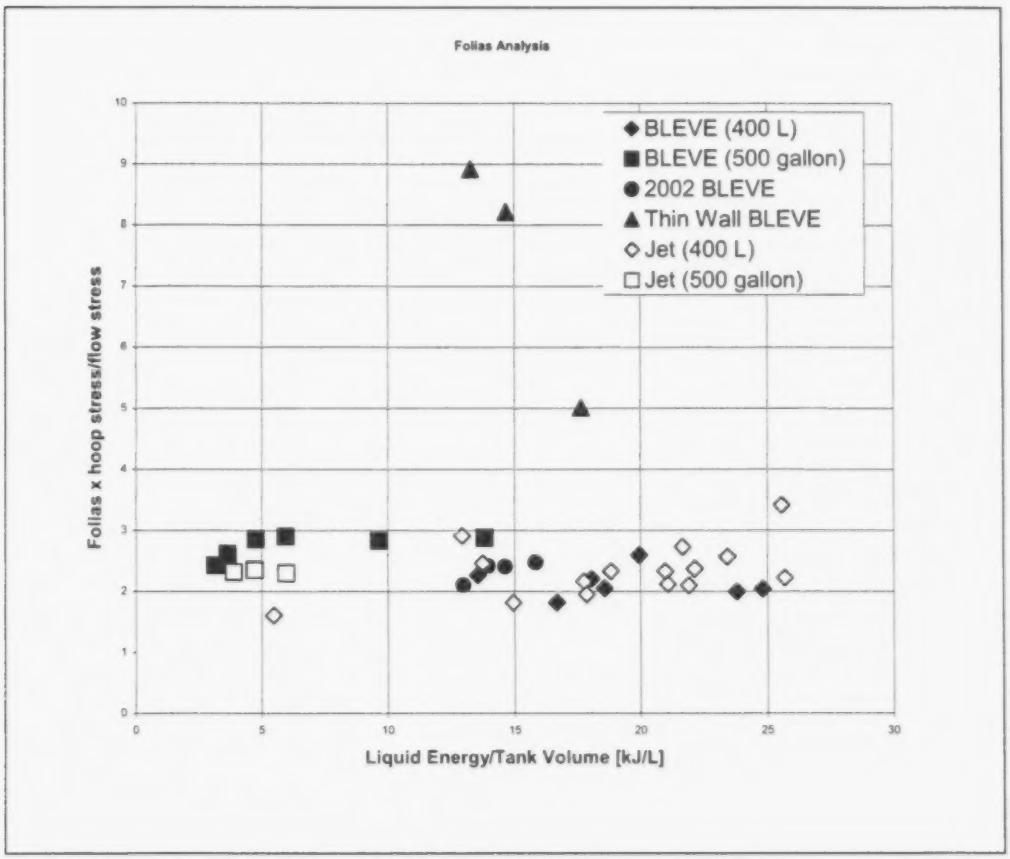

Figure 49: Folias Crack Tip Stress Ratio versus Liquid Energy at Failure

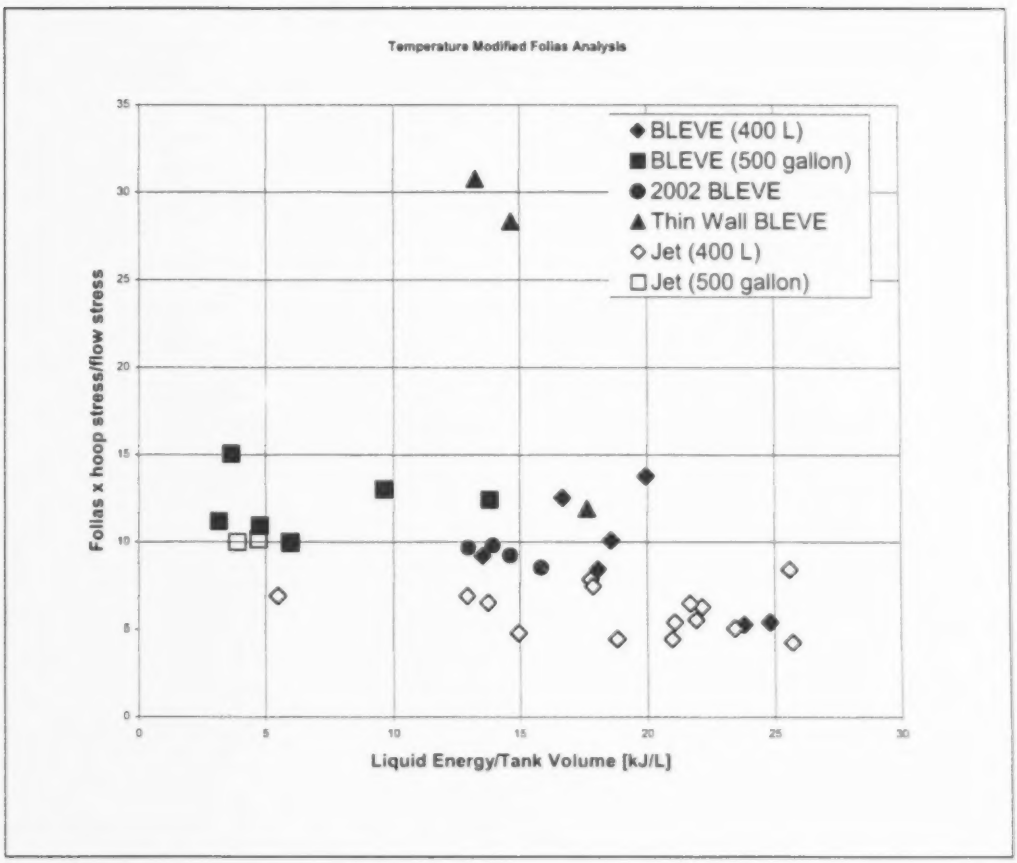

Figure 50: Temperature Modified Folias Crack Tip Stress Ratio versus Liquid Energy at Failure

In an attempt to separate out the BLEVEs from the non-BLEVEs the flow stress was replaced by the material ultimate strength based on the average wall temperature in the severely heated zone. This figure is plotted in Figure 50.

As can be seen, this plot does appear to separate out the BLEVEs from the non-BLEVEs. We also see a general trend towards lower critical crack tip stress at higher liquid energies. From this new plot we have a better method of predicting a BLEVE if we know the tank conditions (fill, average liquid temperature, severely heated length, average wall temperature in heated length, ultimate strength in heated length, and pressure at failure).

5.2 The Role of PRV Blowdown

As seen in the results of this testing, the pressure relief valve plays an important role in the thermohydraulic behaviour of the lading and the survivability of the tank. It is hypothesized that longer PRV cycles associated with larger blowdown are superior to a small blowdown for the same PRV opening pressure for the following reasons:

- Large blowdown results in a lower average pressure and therefore reduced stress and strain on the tank. This reduced stress should give the tank more time to vent its contents because of delayed failure, or possibly no failure.
- There is a lower average liquid temperature and thus it is likely that a larger blowdown will result in a lower liquid temperature at failure. This is shown in Figure 51. A lower temperature at failure results in a lower energy at failure.
- There is a higher chance for stratification, as discussed in Section 4.7 and shown in Figure 52, and this also results in less liquid energy.
- There is an earlier and lower peak energy, as shown in Figure 38.

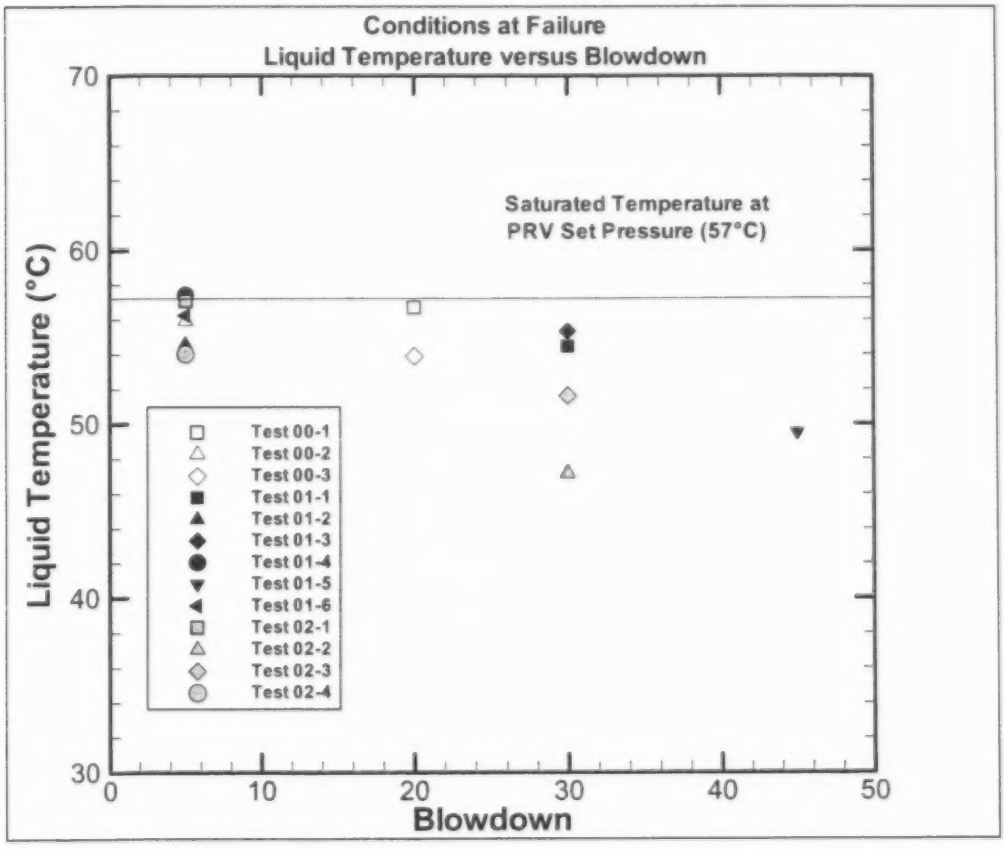

Figure 51: Liquid Temperature at Failure

5.2.1 Improved Survivability

Most of the data backs up the assumption that a larger blowdown improves survivability, but a couple of important discrepancies must be discussed. The following paragraphs discuss five sets of test results, in which each test in a set was completed under similar conditions, except blowdown. From testing in 2001, it was clear that larger blowdown resulted in later failure, but the Set 3 and 4 show the opposite trend. Table 11 shows this data. These sets were previously discussed in Figure 21.

Most likely, the discrepancy seen in Set 3 and 4 was due to inherent variability in data collection. In 2000, perhaps the difference in blowdown (5% versus 20%) was not great enough. The tanks in Set 3 failed at essentially the same time, and it is likely the opposite trend could be seen if the tests were repeated. In 2002, it is believed that blowdown did not have much of an effect on survivability because the tanks were too thin and weak for the fire conditions used. The fire conditions were tuned for 7.7 mm thick walls. These fire conditions were too severe for the 7.1 mm walls in 2002.

In general, the benefits of large blowdown are greater than the benefits of small blowdown. Figure 53 shows the general trend where, if blowdown is increased, survivability will increase.

		Blowdown	Time to Failure	Compared to 5% Test
Set 1	Test 01-2	5%	648 s	-
	Test 01-3	30%	938 s	+44.8%
Set 2	Test 01-4	5%	746 s	-
	Test 01-1	30%	911 s	+22.1%
	Test 01-5	45%	980 s	+31.4%
Set 3	Test 00-2	5%	812 s	-
	Test 00-1	20%	783 s	-3.60%
Set 4	Test 02-1	5%	567 s	-
	Test 02-2	30%	523 s	-7.76%
Set 5	Test 02-4	5%	641 s	-
	Test 02-3	30%	651 s	+1.54%

Table 14: Effect of Blowdown on Tank Survivability

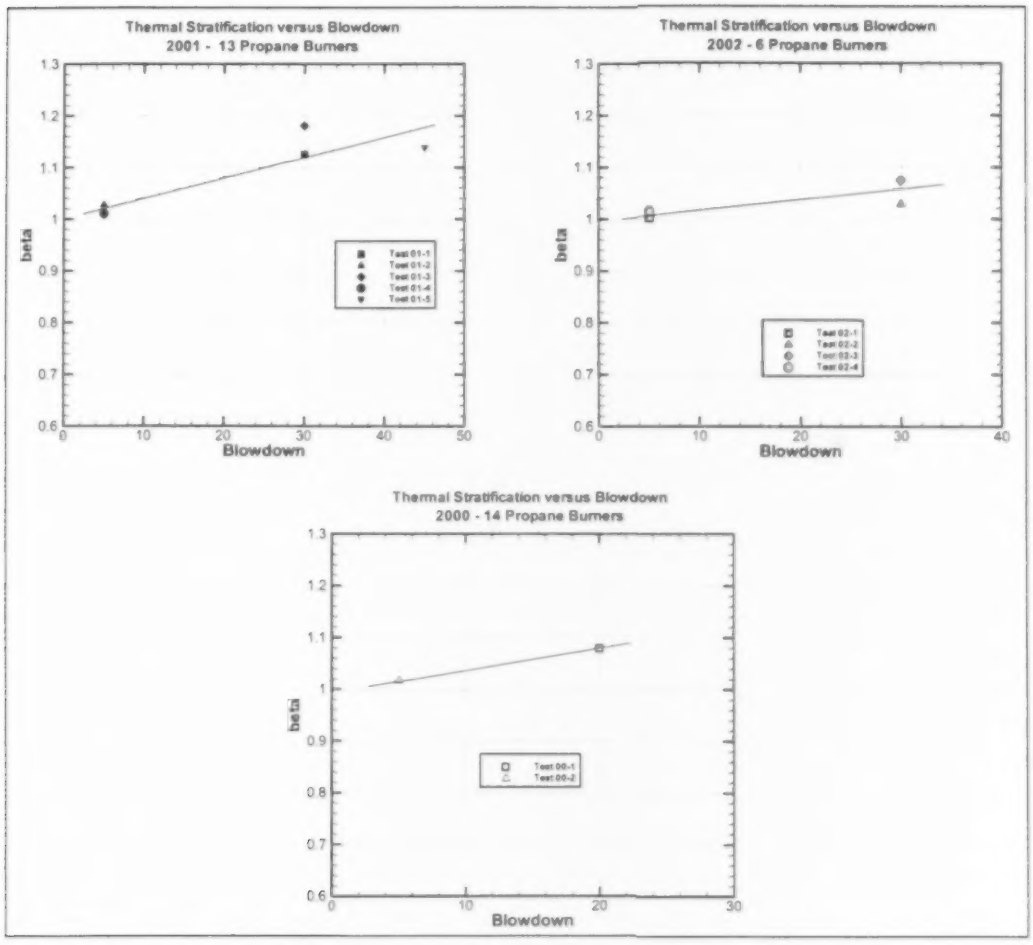

Figure 52: Stratification at Failure

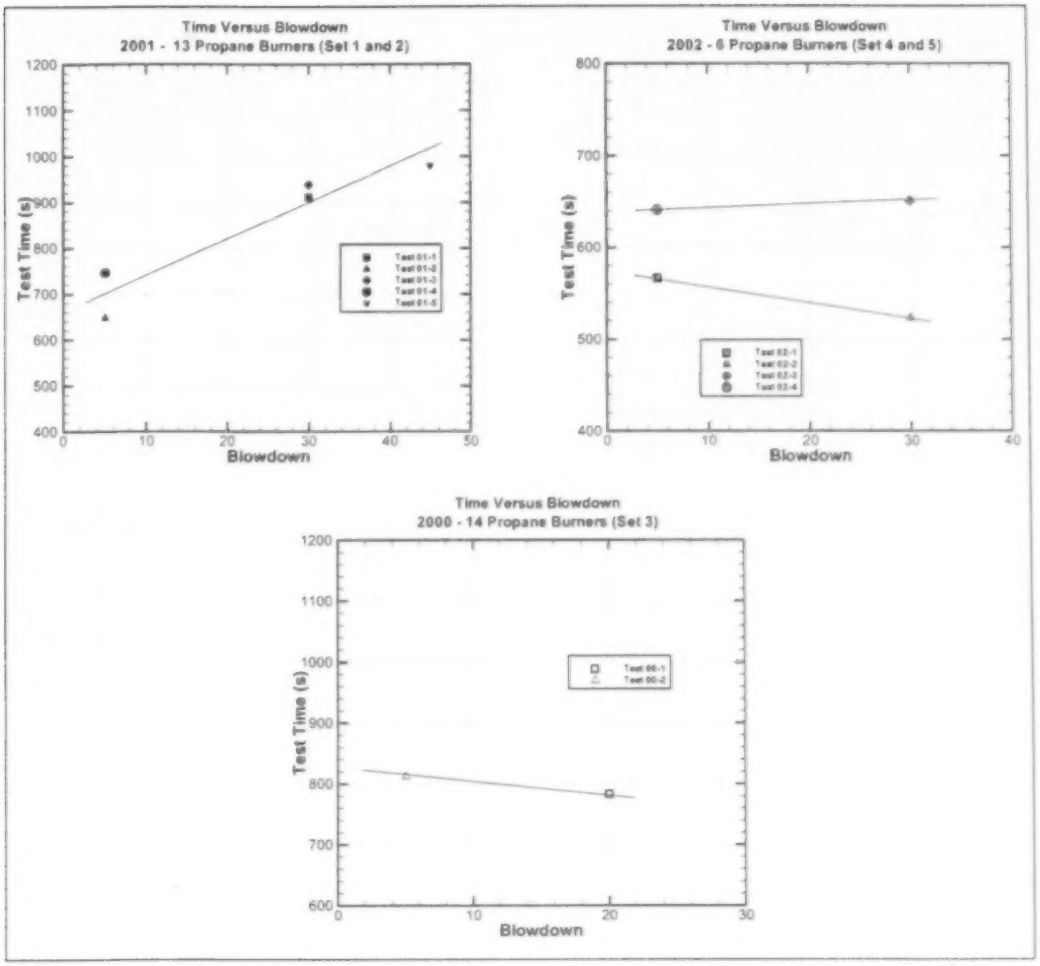

Figure 53: Time to Failure versus Blowdown

5.2.2 Decrease Energy and Hazards at Failure

A later failure due to a larger blowdown results in less energy in the tank at the time of failure because the tank has more time to release the contents through the PRV. Figure 54 shows how the energy available in the tank decreased as time to failure increased. The data from 2001 shows the most significant decrease in energy with blowdown.

The lower energy at failure means less energy available to propagate a crack, accelerate projectiles, propagate a blast wave, and contribute to the fuel for a fireball. A larger blowdown results in less energy available at time of failure. Notice that for the 2002 tests, even though larger blowdown does not improve survivability as seen in Figure 53, the energy available at failure is less for larger blowdowns.

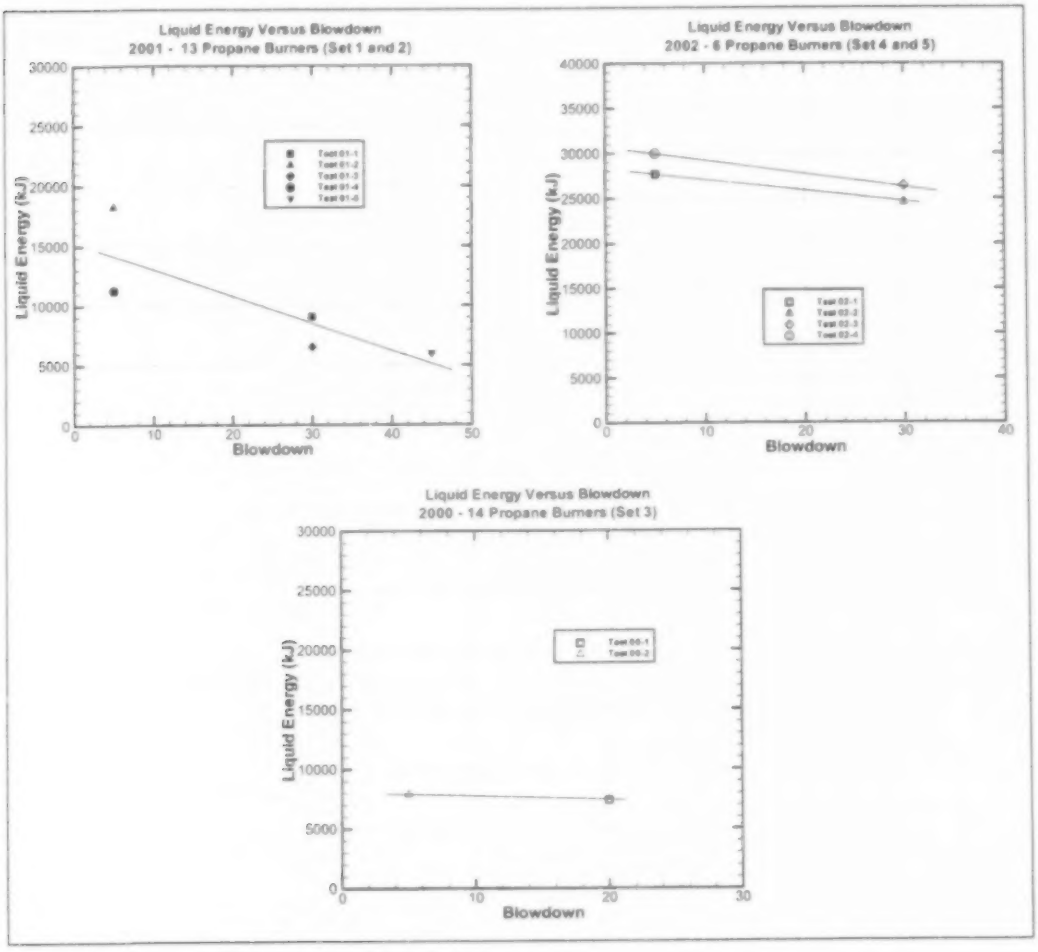
Liquid Energy Versus Blowdown
2001 - 13 Propane Burners (Set 1 and 2)
Liquid Energy (kJ)
Blowdown
Liquid Energy Versus Blowdown
2002 - 6 Propane Burners (Set 4 and 5)
Liquid Energy (kJ)
Blowdown
Liquid Energy Versus Blowdown
2000 - 14 Propane Burners (Set 3)
Liquid Energy (kJ)
Blowdown

Figure 54: Energy at Failure versus Time to Failure

5.3 The Role of Fire Conditions

The effects of the fire conditions on a tank and its contents are harder to quantify than the PRV blowdown. The following are some of the effects of the fire conditions:

- Heat transfer from the fire to the tank lading increases the pressure of the contents.
- Fire on the unwetted wall decreases the strength of the tank wall.
- Fire on the unwetted wall dictates the size of the heat affected zone, and thus, the size of the initial crack. This affects the outcome (BLEVE or jet) of the test as discussed in Section 5.1.
- The heat input rate affects the rate of fluid flow through the PRV.
- The fire distribution affects the temperature gradients within the tank and thus the tank pressurization rate and the fluid motion.

5.3.1 PRV Flow Rate and Cycling Frequency

If the PRV is sized properly or if it is oversized then once activated the PRV will open and close to vent just enough energy to control the pressure. In this case the PRV mass flow is dictated by the fire heat input. If the PRV is too small, then once activated the PRV will remain open and the pressure will continue to rise in the tank. In this case the PRV flow is controlled by the PRV size and the tank pressure.

In these tests the PRV was properly sized and the mass flow increased with an increased heat input rate, as shown in Figure 55. The higher the heat input rate, the faster the tank would empty. If the heat input rate on the vapour space remains constant, a slower mass flow rate will result in more energy stored in the tank at failure.

The higher the heat input to the liquid at the vapour interface, the quicker the tank will pressurize. Quick pressurization is beneficial because that means an earlier PRV pop and the fill level in the tank will start emptying sooner. An earlier PRV pop also means an early warning from the tank that something is wrong. Unfortunately, a quick pressure rise usually occurs in conjunction with a rapid unwetted wall temperature rise and a rapid decrease in tank strength.

A reduced heat input may seem like a safer scenario, but it may also synchronize tank rupture with peak stored energy. A tank partially engulfed in fire may result in a more powerful explosion than a fully engulfed tank.

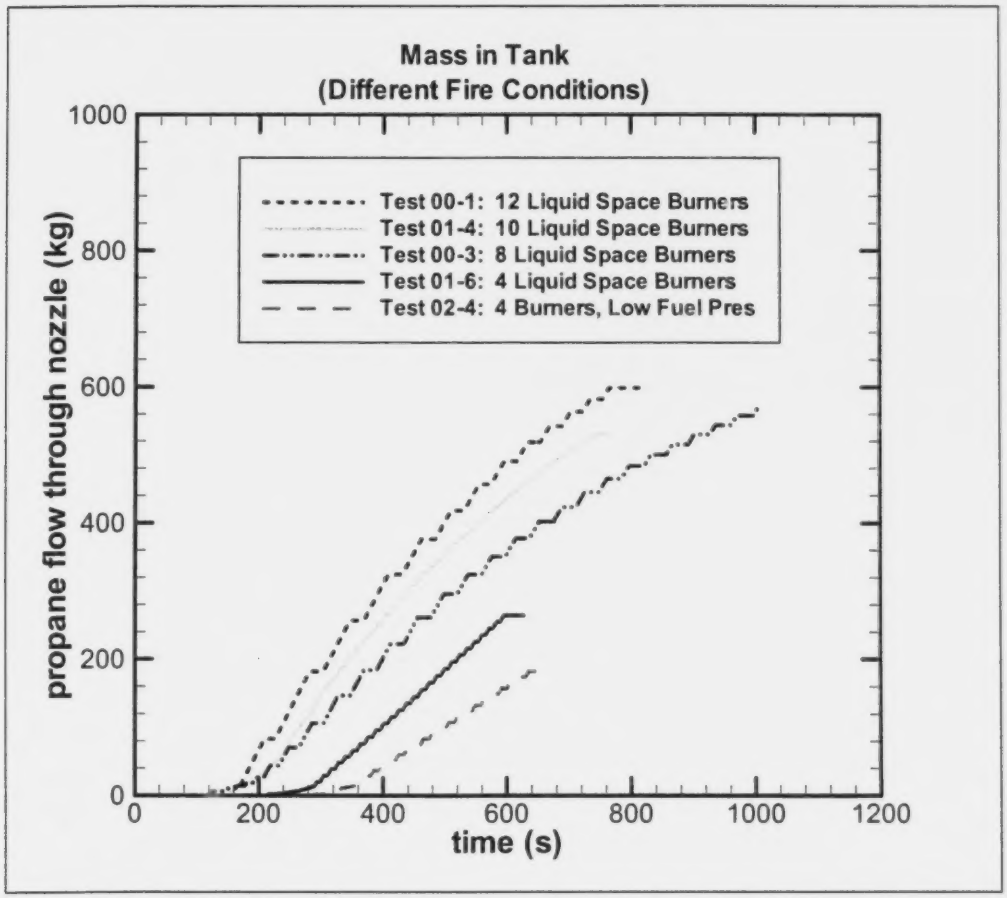

Figure 55: Mass Flow Through Nozzle for Various Fire Condtions

5.3.2 Burner Location/Fire Distribution

Temperature gradients within the tank are developed in the tank according to the fire distribution and thus the fluid motion. In some cases local heating can cause local boiling with liquid swell and frothing against the wall, which plays an important role in transferring heat from the hot walls to the liquid.

When the wall is heated in the liquid space a warm plume of liquid rises from this spot. As this plume rises is mixes partly with the surrounding liquid. If the heated spot is at the bottom of the tank then this plume goes through the cool liquid core and by the time the plume reaches the liquid/vapour interface, much of the heat is dissipated. In this case the pressure will rise slowly in the tank and the liquid will have less temperature stratification. If the heated spot is near the liquid top then little heat is lost to the core and this results in a more rapid pressure rise in the tank. A more rapid pressure rise suggests more temperature stratification.

Figure 56 shows the effect of the number of waist burners (i.e. burners at mid height of tank side) on the pressure rise rate. The pressure rise rate is significantly faster when waist burners are present, as expected. It is interesting to point out that Test 00-3 and Test 00-2 pressurized at the same rate, as indicated in Figure 56, even though Test 00-3 did not have any bottom burners. This is shown in Table 15. This suggests that influence of the lower burners on the pressure rise is almost insignificant if there are waist burners present.

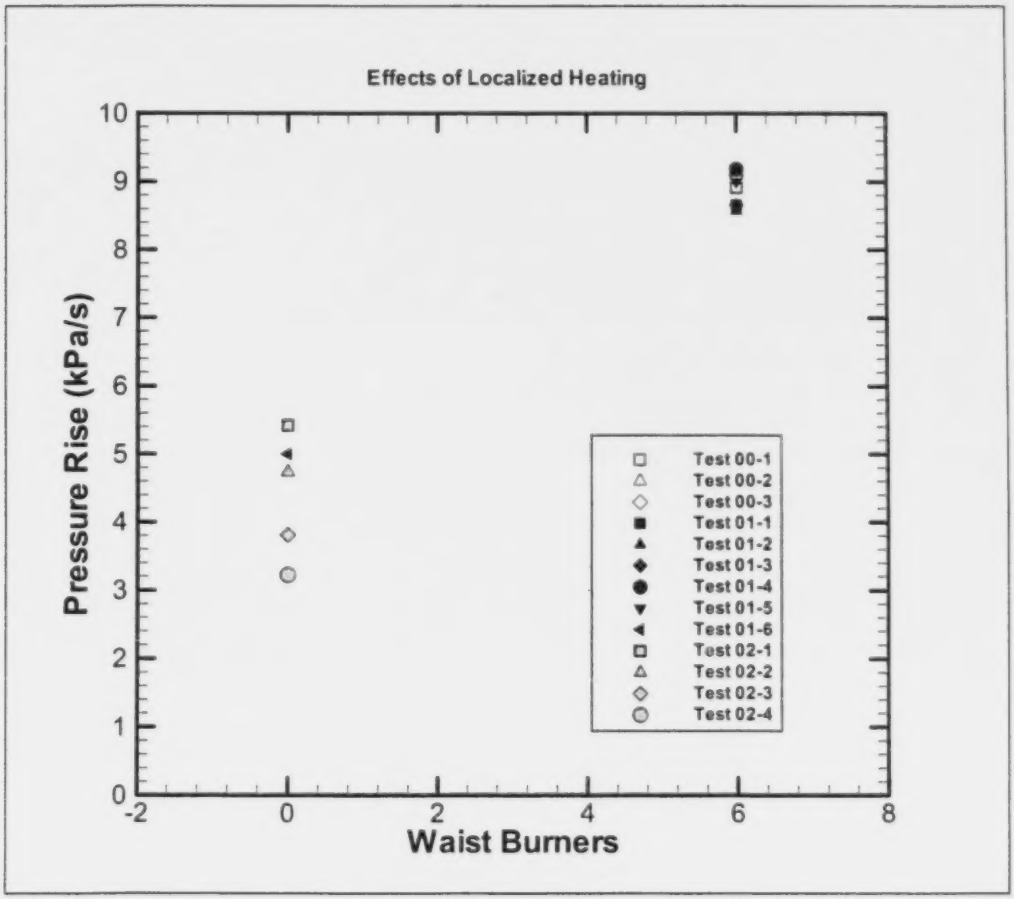

Figure 56: Effect of Burner Location on Pressure Rise

	Waist Burners	Bottom Burners	Pressure Rise (kPa/s)
Test 00-1	6	4	8.9
Test 00-2	6	4	9.1
Test 00-3	6	0	9.1
Test 01-6	0	4	5.0

Table 15: Effect of Waist Burners and Bottom Burners

Comparing Test 00-3 with Test 01-6 demonstrates the importance of burner distribution. Both tests were reduced heating tests, but Test 00-3 had the bottom burners removed and Test 01-6 had the waist burners removed:

- Test 01-6, which only had liquid space burners at the bottom, had the lowest pressure rise, the lowest level of stratification, the highest wall temperatures, and the quickest failure of the standard thickness tanks (2000 and 2001).
- Test 00-3 only had liquid space burners at the waist and had one of the faster pressure rises, the highest level of stratification, the lowest wall temperatures, and the latest failure.

Figure 40 shows the effect of burner location on stratification from these two tests.

It is not a coincidence that the test with the slowest pressure rise was also the test with the lowest stratification. Fire distribution, pressure rise, and stratification are all related. It appears that having large temperature stratification with the bulk of the heat input at the liquid/vapour interface would be the best case to maximize a tank's survivability, because of:

- the high level of stratification
- quick pressure rise and PRV venting
- increased liquid motion for wall cooling

5.3.3 Fuel Pressure

Reducing the burner fuel pressure effectively reduces the heat flux of the utility burners. The reduced fuel pressure in Test 02-3 and Test 02-4 changed the heat transfer to the tank. The lower fuel pressure

- delayed failure
- decreased wall temperature
- decrease pressure rise
- decreased PRV mass flow
- increased fill at failure
- increased energy at failure

The reduced heating rate could actually increase the hazards because of the increased fill and energy at failure.

5.4 The Role of Tank Wall Thickness

As mentioned earlier, the four tanks tested in 2002 were approximately 8% thinner than the previous nine tests. As a result the tanks were weaker and failed earlier, as shown in Figure 57. Also, because the walls were thinner, less energy was required to propagate a crack through the cold steel. This makes a BLEVE failure more probable.

Figure 58 shows two tests with almost identical wall temperatures. Both of these tests had two vapour space burners, but slightly different burner fuel pressure. The thinner wall must have had a slightly less severe fire because other wise the thinner wall would have heated up faster. Test 02-4 failed almost 2 minutes earlier than Test 00-1 because of the thinner wall. The 8% decrease in wall thickness gave a 15% decrease in fail time for the same wall temperature.

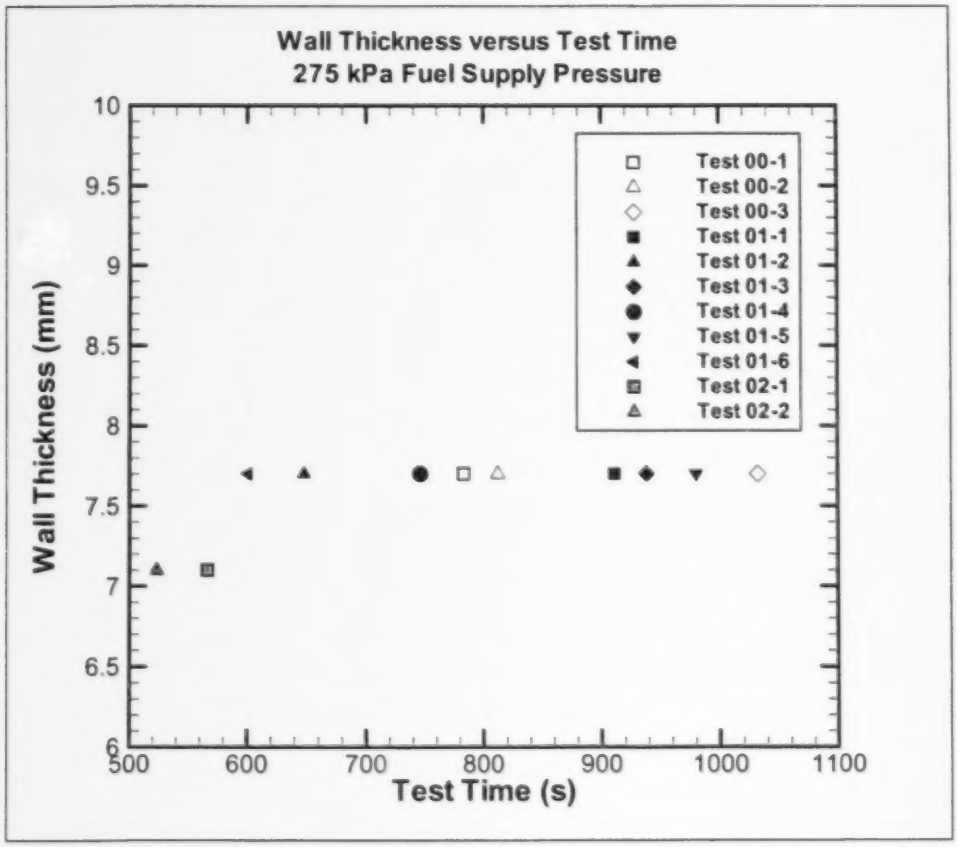

Figure 57: Wall Thickness versus Test Time

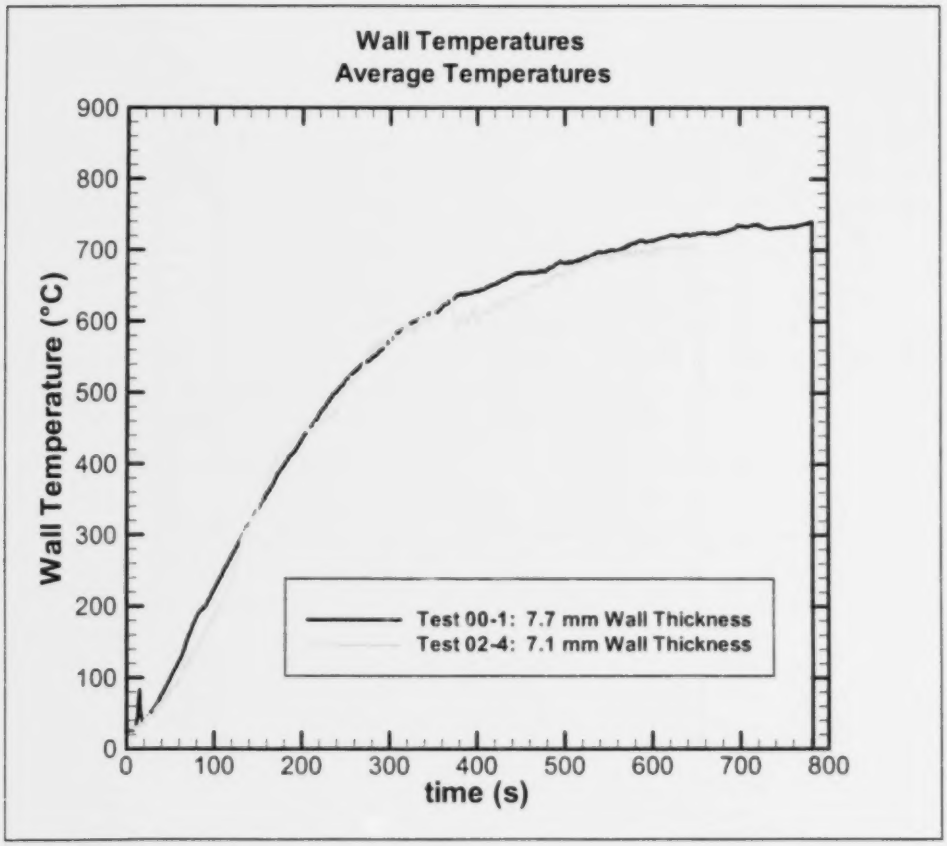

Figure 58: Effect of Thinner Wall on Test Time

5.5 Uncertainties and Error Sources

5.5.1 Possible Uncertainty Sources

There are several areas in this test series that contain possible error sources or uncertainties. There were two sources of error observed in the tests:

- errors associated with the accuracy of the instruments
- errors associated with the instrument installation

Some of these uncertainties are listed below:

- **Vapour Space Wall Thermocouples**. Conduction error can be significant when dealing with measuring wall temperatures in fire. Using ceramic insulation and a steel

jacket to hold the insulation in place, as was done in this testing, will reduce this error to about +10°C.

- **Lading Temperature and Pressure**. The errors associated with measuring the temperature and pressure in the lading and nozzle were relatively small (about 1-2 °C and about 10 kPa)
- **Lading Thermocouple Location**. An uncertainty results from the difficulty in determining exactly when a thermocouple moves from the liquid to the vapour and the errors in the installed thermocouple height. This error is assumed to be +/- 1 cm.
- **Fill Level**. Each test started with 1500 litres +/- 5 litres of propane. The purging process removed 40 litres +/- 5 litres. It is estimated that the initial volume of the liquid propane in the tank after purging is 1460 litres +/- 10 litres. This corresponds to a mass of +/- 5.0 kg assuming the liquid propane was at 20°C.
- **Air Purge**. It is possible that some air remained in the tank after the purging process. This may have had a small effect on the time to the first PRV pop. This air would quickly be lost once the PRV was activated.
- **Leak at PRV Coupling**. There was evidence of a propane leak at the PRV Coupling. This would affect the estimated mass at failure calculation. The mass loss through the leak is considered to be insignificantly small.
- **Wall Thickness**. This is discussed in more detail in the next section.

5.5.2 Differences in Wall Thickness

It was desired for all the tanks to have the same wall thickness. Unfortunately, the tank wall thickness in 2002 was almost 8% thinner than the tanks in 2000 and 2001. The tanks from 2000 and 2001 were all made from the same steel lot. The manufacturer, however, was unable to make the 2002 tanks from the same lot. The tanks were all made according to the same specifications, but unfortunately the drawings only called for a minimum wall thickness. In 2002, the tank walls were rolled to a thickness closer to the minimum allowable thickness.

After the tests were complete, wall thickness was measured from each test. It was found that the average wall thickness for 2000 was 7.7 mm while the average wall thickness for 2002 was 7.1 mm. Unfortunately, the wall thickness of the 2001 tanks was never confirmed before they were scrapped.

This difference in wall thickness is very disappointing because wall thickness greatly influences tank strength and has a significant effect on test results.

For a more complete error analysis see Appendix H.

5.6 Practical Fire Considerations

It is desired to consider how the results would be different if we looked at a propane tank in a real fire situation. There are many things that could be discussed in this section, but only a selected few things will be mentioned.

1. **Spring Softening**. In a real fire situation, the spring on the PRV relaxes at higher temperatures. If there is a higher vapour temperature, there will be a higher change of spring softening, which effectively results in a reduced pop and resealing pressure. This would be another benefit of large blowdown (See Figure 29) because of the higher vapour temperature at the PRV, although this was not seen in this test series.

2. **Locally Heated Tanks: Is a Burner Fire Realistic?** In a real fire situation, fire is more evenly distributed and this fire distribution will influence the test results. Using burners to simulate the fire is a useful practice because of the repeatability, but also gives excellent data on locally heated propane vessels. This data is very useful in insulation deficiency and thermal protection studies. As mentioned in Section 5.3.2, the location of the burner (or insulation deficiency) makes a difference in heat transfer and pressure and temperature rise rates.

3. **Large Blowdown – is it practical ?** It has been argued that an increased blowdown results in improved survivability. This may suggest that a 100% blowdown, such as a fusible plug would be the best alternative towards making PLG storage safer. Some believe that a large blowdown is a problem, however, if there is an accidental opening. In the 45% blowdown test (Test 01-5), the valve remained open for over 5 minutes (316 seconds) after its initial pop. In this time 275.3 kg of propane was vented, corresponding to 37.7% of the initial lading mass. However, this in no way is the same as an accidental opening without fire. If a tank heats up in the sun the PRV will open due to liquid temperature stratification. Once the PRV opens the pressure will drop rapidly and the PRV will reclose quickly even if the blowdown is large. Recall that the PRV will only stay open for a long period if the bulk liquid is heated. Also recall that the PRV flow is determined by the heat input. A tank sitting in the sun will vent the same mass of propane in one hour regardless of the blowdown. The flow per pop is larger for the large blowdown – but the small blowdown PRV will pop more times per hour.

6.0 Conclusions and Recommendations

The ultimate goal of these fire tests was to better understand what happens when a tank becomes engulfed in fire and how the PRV blowdown affects the outcome. This was done in order to learn how to minimize the potential hazards. This chapter summarizes the findings and discusses areas in this research field that still need to be studied.

6.1 Conclusions

In the tests discussed in the previous chapters, the tanks were exposed to fires that were as similar as possible. The fire conditions and the PRV blowdown were varied. Three tests resulted in transient jet releases, while the remaining ten tests resulted in BLEVEs of various strengths depending on the fill and stored energy at failure.

The following conclusions can be made about the PRV blowdown:

- The blowdown behaviour affects the result of fire impingement and therefore the variability in PRV blowdown seen in PRV testing is significant.
- A large blowdown is beneficial because it leads to:
  - lower average pressure
  - lower average liquid temperature (lower liquid energy)
  - greater stratification at failure (lower liquid energy)
  - lower and earlier peak energy
  - higher chance of spring softening due to a higher average vapour temperature
- Large blowdown tends to increase the vapour space temperature, which may increase the vapour space wall temperature. This was not seen in our test series.
- For similar fire conditions, increasing the blowdown tends to improve the survivability (i.e. delay failure in most cases) of a propane tank in fire and allows for more time to react and evacuate or for emergency response personnel to do their work.
- Due to delayed failure, increasing the blowdown results in less mass and energy in the tank at failure, which reduces the hazards.
- Less mass available at failure means a lower fill and a less energetic boiling response upon sudden depressurization.
- Less energy available at failure means less energy available to propagate a crack. It is hypothesized that the blowdown could make the difference between a BLEVE and a non-BLEVE failure, although this was not shown in the present tests.

The following conclusions can be made about the fire conditions:

- For a properly sized or oversized PRV, the PRV mass flow rate out of the tank is proportional to the heat input to the tank. The larger the fire, the faster the tank empties.
- The heat input distribution affects the temperature gradients inside the tank and affects the overall outcome.
- A fire that impinges near the liquid/vapour interface leads to:
  - greater stratification

  - faster pressure rise
  - earlier initial PRV opening
  - more fluid motion at the interface for vapour space wall cooling
- The worst case fire is not always a fully engulfing fire. A partially engulfing fire has a chance of causing failure at the point in time where the lading energy is maximized. This will result in the strongest hazards and the highest chance of a BLEVE.
- An additional vapour space burner did not affect wall temperature at failure, but did increase the size of the heat affected area.
- Increasing the heat affected area in the vapour space by increasing the number of burners made the difference between a BLEVE and a non-BLEVE failure.

The following conclusions can be made about tank failure:

- The time to initial failure depends on the fire conditions and on the design of the tank and pressure relief system.
- If a rupture takes place in a vessel holding a liquid at or near its atmospheric superheat limit, it will not always produce a BLEVE.
- BLEVEs were observed with liquid temperatures between 47 and 58°C. (The atmospheric superheat limit is 53°C.)
- BLEVEs were observed with fill levels between 12 and 61%.
- For the specific conditions used in this test (i.e. intense local heating in the vapour space), the tank failure was better predicted by assuming failure occurs when the nominal hoop stress exceeds 150% of the material ultimate strength in the heated zone. Using the typical failure criteria (hoop stress exceeds ultimate strength) grossly underpredicted failure times.
- It was possible to produce a plot based on a modified Folias analysis that divided BLEVE and non-BLEVE outcomes. If this plot proves to be correct, then it can be used to predict a BLEVE outcome if the properties of the heated zone and the liquid energy conditions are known.

These conclusions apply for the fire conditions tested. Caution should be used when extrapolating these results to other conditions. The effect of blowdown may not be the same for other types of fire exposure. Further testing is necessary to consider other credible fire conditions.

6.2 Recommendations

The optimum setting for PRVs (flow area, set pressure, blowdown) has been debated for a long time. This study suggests that the *blowdown should be set as large as practically possible, while the opening pressure is set as low as practically possible*. The following additional recommendations are made.

- Standards should reflect the important role of blowdown.
- Valves should be manufactured so that they have a predictable and repeatable performance.
- Further testing should be done to see the effect of blowdown in other fire situations.

There is a trend in current standards to use computer models to qualify thermal protection and PRV systems. This is done because of the high cost of testing. The results from this test series provide useful data for the testing and validation of such models, specifically:

i) effect of fire location on tank pressurization rate
ii) effect of fire location on vapour space temperatures
iii) fire location and PRV behaviour on temperature stratification and lading energy
iv) tank failure due to local heating

Researchers should continue to study additional parameters that affect the outcome of fire engulfment and try to develop innovative new methods to minimize the risks and hazards. Although PLG containment accidents do not occur that often, the consequences can be devastating and active research must try to further reduce the number of incidents.

6.3 Future Work

There is current interest in insulation defects resulting in localized heating and effects on tank and lading response. This data can be used to study the effect of localized heating. The data could also be used to help validate computer models of propane tanks with insulation deficiencies.

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Appendix A: Design Calculations and Notes

Fire Conditions

The design criteria for the propane burner array required that the burners heat the vessel at the same rate as a fully engulfing fire at 816°C (1500°F). It was calculated that approximately 13 or 14 burners will accomplish this, as shown below.

Engulfing Fire

The calculations are based on the following assumptions:

- Fire acts as a black body.
- The steel surface emissivity was $\varepsilon = 0.9$.
- The view factor from the fire to the tank was $F_{12} = 1.0$.
- Heat transfer is dominated by radiation. Convective heat transfer is negligible.

The heat transfer from the fire to the tank was calculated using the formula below:

$$Q_{engulf} = Q_{12} = A \cdot \varepsilon \cdot \sigma \cdot F_{12} \cdot (T_{fire}^4 - T_{tank}^4)$$

Where σ is the Stefan-Boltzmann constant. The surface area of the tank is approximately 9.2 m² and the initial tank temperature was taken to be 300 Kelvin. This gives a total heat transfer of 655.8 kW.

$$Q_{engulf} = 655.8kW$$

Torch Fire

To calculate the heat transfer in the torch fire, the following assumptions were made.

- Torch fire has a flame temperature of T_{fire}=1300K.
- A convective heat transfer coefficient of $h = 200Wm^{-2}K^{-1}$ was used.
- The view factor to the cool surroundings was 0.75.
- Each torch impinges on an area of 0.2 m².

The following equation was used to calculate the convective and radiative heat transfer:

$$Q_{torch} = Q_{rad} + Q_{conv} = A \cdot \varepsilon \cdot \sigma \cdot F_{12} \cdot (T_{fire}^4 - T_{tank}^4) + A \cdot h \cdot (T_{fire} - T_{tank})$$

It was calculated that the heat transfer from one torch was 47.6 kW per burner.

$$Q_{torch} = 47.6kW / burner$$

To determine the required number of burners, the following calculation was completed:

$$N_{burners} = \frac{Q_{engulf}}{Q_{torch}} = 13.8 \text{ burners}$$

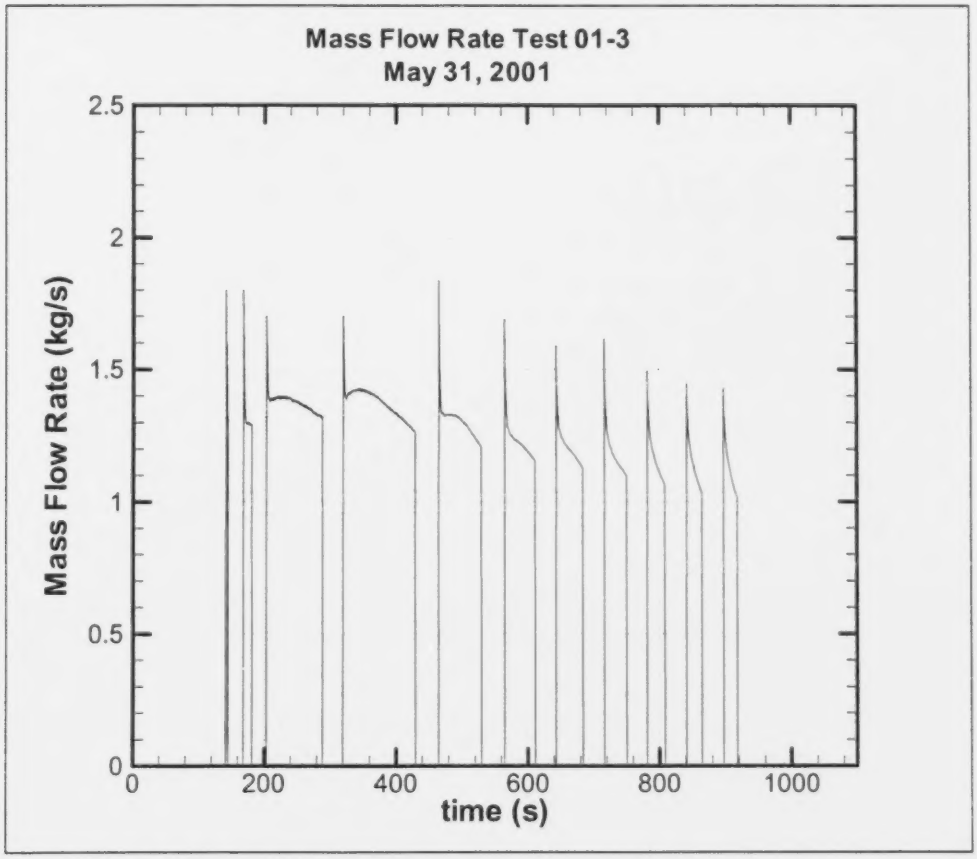
Approxmately 13 or 14 burners will simulate a fully engulfing fire at 816°C.

Pressure Relief System

The goal of the pressure relief system was to mimic a real pressure relief valve.

- The PRVs normally used in the test tank is rated for 2565 scfm (standard cubic feet per minute) of air at 300 psi gauge (250 psi + 20% overpressure).
- Using the density of standard air (1.2 kg/m^3) this corresponds to 1.49 kg air/s.
- Assuming a flow coefficient through the original PRV of approximately 80% and air at 300 psi and 25°C, the effective nozzle diameter is calculated to be 21.6 mm.
- Using the same valve, propane at 275 psi and 150°C would be discharged at 1.35 kg propane/s.

The figure below shows that the calculated propane flow rate was attained in the tests.

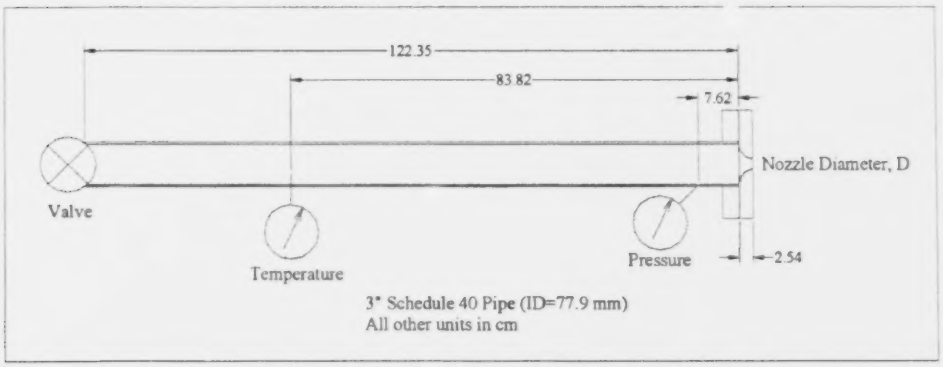


Acutal Recorded Mass Flow Rate versus Time

Given that a smooth coverging nozzle with a high flow coefficient (0.99) was used in the field testing, the nozzle throat diameter can be calculated.

- Using propane at 275 psi and 150°C and a valve with a 99% flow coefficient, a nozzle diameter of 19.4 mm was calculated.

The original nozzle used in the first summer of testing was 24 mm. In order to reduce the frequency of the valve cycling, a 21 mm nozzle was used in 2001 and 2002.



PRV Nozzle (Instrumented for Mass Flow Calculations)

The computer controlled PRV and flow nozzle had to be placed behind a concrete wall and a pipe was required to connect the vapour space with the valve. Too big of a pipe size resulted in a significant increase in the size of the vapour space, while too small of a pipe resulted in too many losses through the pipe. When the first set of tanks were originally ordered, it had been decided that 1.5 inch pipes were going to be used. The optimum pipe size was later found to be a 2 inch Schedule 40 steel pipe. This resulted in a different sized coupling on several of the tanks. This coupling size did not affect the flow behaviour, however, because the flow was choked at the nozzle. (It is believed that the bigger coupling did have an effect on the path the crack travelled, however, after the tank failed.) All thirteen tests were completed with a 2 inch pipe connecting the valve to the vapour space.

In a real accident scenario, a PRV will sometimes see two phase flow if the tank is very full when the PRV first opens. Any liquid that exits the tank in the experimental set up, however, is going to evaporate before the valve. The calculations presented in this thesis assume a single-phase flow.

The nozzle was manufactured according to ASME fluid meter standards. The figure shows proper dimensions.

Fire Ignition System

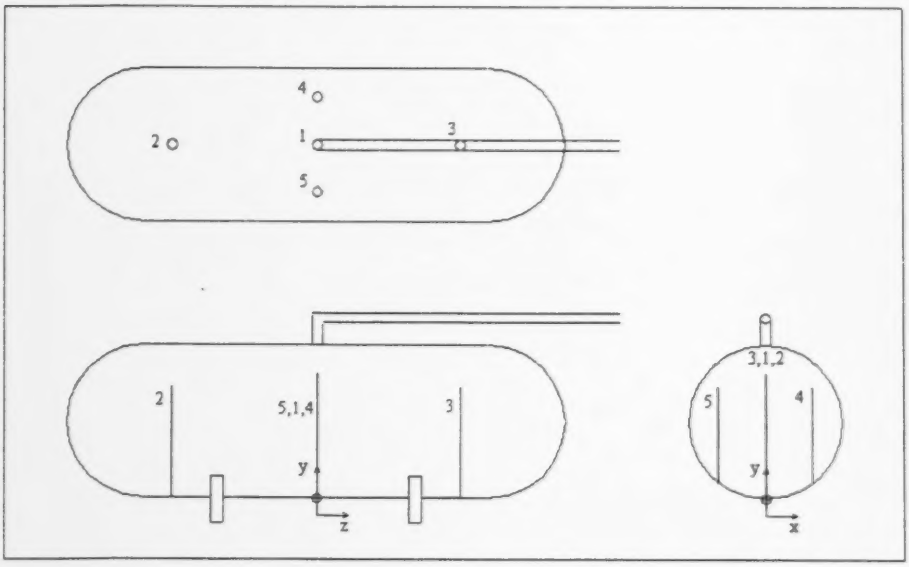
A dependable and repeatable method for remote ignition, even with high wind speeds was required. This was accomplished using high voltage ignitors from gas stoves. High voltage spark plug cable was used to carry the charge from the ignitor to the burner. A small gap between the ignition wire and the grounded metalic burner resulted in sparking. This sparking provided enough energy for ignition.

Fuel Delivery System

For safety reasons, the fuel supply for the liquid propane burners was located behind a concrete slab wall, approximately 50 metres from the tank. Hoses, pipes, a computer controlled valve, manual valves, and a pressure regulator were required to deliver the liquid propane to the burners. Just like the burners and burner stands, the fuel distribution lines were designed to break at a convenient location and were easily replaceable in the field. The pipes were placed along the ground and were held in place with sand bags.

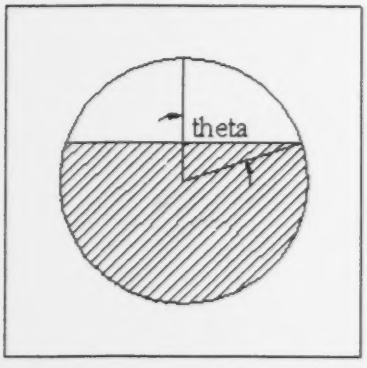
Appendix B: Thermocouple Location

The following figure shows the location and number for the five thermocouple bundles.



Thermocouple Bundle Location

The following figure shows how the fill angle is defined.



Fill Angle

The following table gives the bundle number and Cartesian coordinates for each thermocouple.

t/c	fill	B#	x(in)	y(in)	z(in)	t/c	fill	B#	x(in)	y(in)	z(in)
T0	0.9	1	0	30.9	0	T24	0.1	2	0	6.1	-35
T1	0.8	1	0	27.3	0	T25	0.8	3	0	27.3	35
T2	0.75	1	0	25.7	0	T26	0.75	3	0	25.7	35
T3	0.7	1	0	24.2	0	T27	0.7	3	0	24.2	35
T4	0.65	1	0	22.7	0	T28	0.65	3	0	22.7	35
T5	0.6	1	0	21.3	0	T29	0.6	3	0	21.3	35
T6	0.55	1	0	19.9	0	T30	0.5	3	0	18.5	35
T7	0.5	1	0	18.5	0	T31	0.4	3	0	15.7	35
T8	0.45	1	0	17.1	0	T32	0.25	3	0	11.3	35
T9	0.4	1	0	15.7	0	T33	0.1	3	0	6.1	35
T10	0.35	1	0	14.3	0	T34	0.8	4	11.5	27.3	0
T11	0.3	1	0	12.8	0	T35	0.75	4	11.5	25.7	0
T12	0.25	1	0	11.3	0	T36	0.6	4	11.5	21.3	0
T13	0.2	1	0	9.7	0	T37	0.5	4	11.5	18.5	0
T14	0.15	1	0	8	0	T38	0.4	4	11.5	15.7	0
T15	0.1	1	0	6.1	0	T39	0.25	4	11.5	11.3	0
T16	0.8	2	0	27.3	-35	T40	0.1	4	11.5	6.1	0
T17	0.75	2	0	25.7	-35	T41	0.8	5	-11.5	27.3	0
T18	0.7	2	0	24.2	-35	T42	0.75	5	-11.5	25.7	0
T19	0.65	2	0	22.7	-35	T43	0.6	5	-11.5	21.3	0
T20	0.6	2	0	21.3	-35	T44	0.5	5	-11.5	18.5	0
T21	0.5	2	0	18.5	-35	T45	0.4	5	-11.5	15.7	0
T22	0.4	2	0	15.7	-35	T46	0.25	5	-11.5	11.3	0
T23	0.25	2	0	11.3	-35	T47	0.1	5	-11.5	6.1	0

The following table shows which thermocouples are in each thermocouple bundle.

fill	angle (°)	height(in)	Centre	Sides	Ends
10%	132.1	6.1	x	x	x
15%	124.6	8	x		
20%	118.4	9.7	x		
25%	113	11.3	x	x	x
30%	107.9	12.8	x		
35%	103.2	14.3	x		
40%	98.7	15.7	x	x	x
45%	94.3	17.1	x		
50%	90	18.5	x	x	x
55%	85.7	19.9	x		
60%	81.3	21.3	x	x	x
65%	76.8	22.7	x	x	
70%	72.1	24.2	x	x	
75%	67.1	25.7	x	x	x
80%	61.6	27.3	x	x	x
90%	48	30.9	x		

Appendix C: Test Summaries

Test 00-1

- 2000 Baseline Test, August 31, 2000
- 20% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 24 mm Nozzle Diameter
- 12 burners on liquid space, 2 burners on vapour space
- 19°C

This tank failed with a large finite failure (27 inches) and a massive jet after 13.0 minutes. Thrust from the massive jet caused the tank support leg to buckle and this allowed the tank to roll off of the stands.

Test 00-2

- Reduced Blowdown Test, September 7, 2000
- 5% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 24 mm Nozzle Diameter
- 12 burners on liquid space, 2 burners on vapour space
- 10°C

This tank failed after 13.5 minutes with a small finite failure (8.5 inches) and a jet flare. The lower initial temperature could be significant in this test.

Test 00-3 Tank (Fish Mouth)

Test 00-3

- Reduced Heating Test, September 13, 2000
- 20% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 24 mm Nozzle Diameter
- 8 burners on liquid space (four lower burners removed), 2 burners on vapour space
- 17°C, wind speed of greater than 21 km/h

This tank failed after 17.2 minutes with a large 21.5 inch failure and a massive jet. This test experienced strong winds which are probably responsible for the lower indicated wall temperature.

Test 01-1

- 2001 Baseline 30% Blowdown Test, May 24, 2001
- 30% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 10 burners on liquid space, 3 burners on vapour space
- 24°C, 15 km/h east wind, blue skies

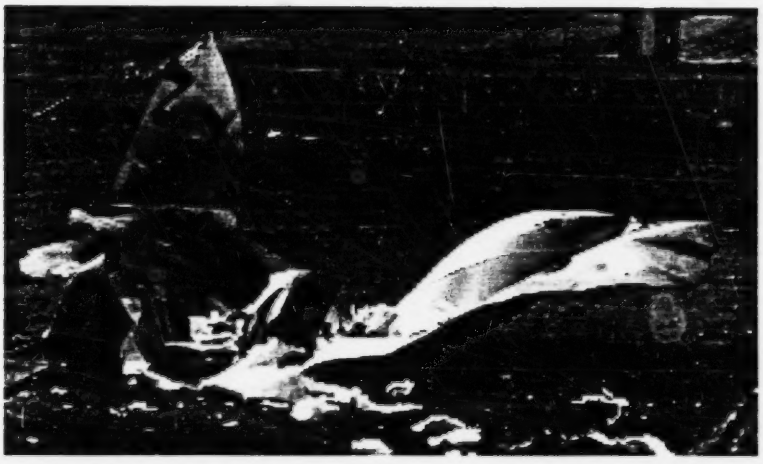
Everything worked as planned except a small propane leak at the PRV joint at the tank. This produced a small fire at that location which probably did not have any effect on the tank failure. The tank BLEVEd in approximately 15.2 minutes. The failure started as a jet release lasting about 1.2 seconds and this quickly progressed to a total loss of containment and BLEVE. The noise produced by the BLEVE was a sharp crack (high pitched sound) at the observation position suggesting a steep shock front.

In this test, the end of the tank that was under the burners was flattened, while the far 1/3 of the tank remained cylindrical. The tank remained in one piece. The crack started under the burners and propagated to the tank end and around the end weld. The crack propagated towards the PRV fitting where it was deflected and traveled towards the tank bottom.

Test 01-2

- 2001 Baseline 5% Blowdown Test, May 29, 2001
- 5% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 10 burners on liquid space, 3 burners on vapour space
- 13°C, 12 km/h southwest wind along tank axis, cloudy

Test 01-2 Fireball



Test 01-2 Flattened Tank

The upper-centre-side burner on the right side seemed to be running at reduced power as indicated by less blackening of the wall at that location. This may have reduced the heat input rate and thus the rate of emptying of the tank. The tank failed at 10.8 minutes and produced a rapid type BLEVE with little or no initial jet release. The explosion was a

powerful BLEVE and was characterized by a loud boom suggesting a shock with strong impulse load. In fact, the blast damage was much more severe than in Test 01-1. Windows in the tool shed were broken and the data acquisition box was knocked off the wall mounting in the instrument bunker.

After the test the failed tank looked very similar to the tank in the previous test, except the unflattened cylinder was separated from the flattened part. The end piece rocketed off the concrete wall and landed approximately 50 metres from its initial location.

Test 01-3

- Repeated 30% Blowdown Test, May 31, 2001
- 30% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 10 burners on liquid space, 3 burners on vapour space
- 19°C, 12 km/h north wind, few white clouds

This tank BLEVEd in 15.6 minutes, which compares to 15.2 minutes in Test 01-1. This agreement is important since the wind conditions were somewhat different. The wind was 10-20 km/h along the tank axis, similar to the wind conditions in Test 01-2.

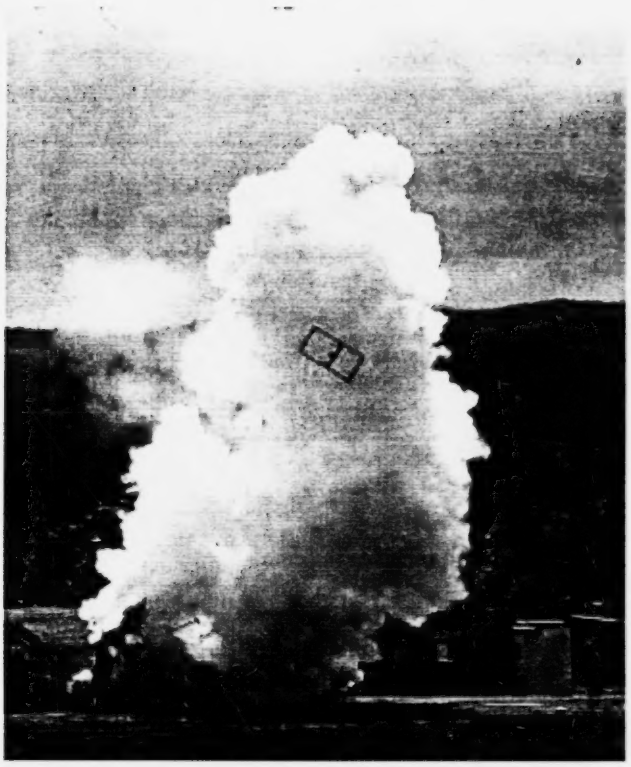
With this late failure the tank fill was low and therefore the fireball was small. The BLEVE was a single-step, rapid type failure with no initial jetting. This late failure agreed well with Test 01-1 except that Test 01-1 had an initial jet, which suggests the crack needed some help from the boiling response of the remaining liquid to continue to grow.

Test 01-4

- Repeated 5% Blowdown Test, June 6, 2001
- 5% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 10 burners on liquid space, 3 burners on vapour space
- 20°C, 13 km/h northwest wind across tank axis, overcast

Test 01-4 was a repeat of Test 01-2. The test lasted 12.4 minutes and like Test 01-2 ended with a BLEVE. This early failure agrees well with Test 01-2 and suggests that small blowdown does lead to earlier failure with stronger hazards. However 12.4 minutes was 1.6 minutes later than Test 01-2, which failed at 10.8 minutes. The difference in test time is probably due to the difference in wind conditions.

The tank was fully opened and flattened except for 15% of one end. The total opening of the tank suggested a powerful failure. The BLEVE was unusual in that the propane did not ignite and there was no fireball or fire after the failure.



Test 01-4 Propane Cloud (No Ignition)

Test 01-5

- Increased Blowdown Test, June 7, 2001
- 45% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 10 burners on liquid space, 3 burners on vapour space
- 20°C, 8 km/h northwest wind across tank axis, blue sky

This test was the longest test, ending with a BLEVE after 16.3 minutes. As a result of the late failure, the tank had a very low fill level. The PRV cycles were very slow due to the pressure leveling off with the very large blowdown. This long period of reduced pressure is probably the reason for the late failure. The late failure also ensured very high wall temperatures, which explains the total failure of the vessel. The resulting fireball was small and of short duration due to the small amount of liquid present.

The tank failure was catastrophic with perfect symmetry. The tank end was split in half at the heated end. The crack followed the tank top centre and split and turned and followed near the weld on the end. The cylinder was totally flattened.

Test 01-5 Fireball

Test 01-5 Tank

Test 01-6

- Reduced Heating Test, June 12, 2001
- 5% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 4 burners on liquid space (waist burners removed), 3 burners on vapour space
- 18°C, 6 km/h northeast wind along tank axis, overcast

Test 01-6 Fireball

The final test of the 2001 test series, Test 01-6 was conducted with only four liquid level burners. The wind was very light at 0-5 km/h. The test ended 10 minutes later with a 1.6 second initial jet followed by a very powerful BLEVE with a large, long-duration fireball. The blast wave broke the tool-shed window and the data acquisition box was knocked off the wall. A TV monitor was also knocked off the desk onto the floor. Because the failure was early, there was a large amount of liquid still in the tank at failure (approximately 50% full.) The early failure and the low liquid heating rate combined to give a very powerful BLEVE outcome with the tank flattened on the ground and the concrete pad being severely damaged.

In this test the PRV was late to open because of the reduced heating rate. This resulted in very high vapour space temperatures, which resulted in even higher vapour space wall temperatures. When the PRV did open, the vapour space wall temperatures dropped due to the increased convection and the cooler vapour.

Test 02-1

- 2002 Baseline 5% Blowdown Test, June 17, 2002
- 5% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 4 burners on liquid space (waist burners removed), 2 burners on vapour space
- 11°C, 5 km/h east wind, overcast
- thin tank

The first test of the 2002 series was to repeat Test 01-6 with only two vapour space burners. The test ended very early (9.4 minutes) with a very powerful BLEVE. There

was an initial jet of 1.9 seconds and a long-duration, beautifully spherical, hemispherical fireball. The blast wave broke all the windows in the instrument bunker and tool shed and knocked several things off the tables. A propane burner fell through the roof of the tool shed. The tank was flattened on the ground with both end caps flung off.

Test 02-1 Fireball

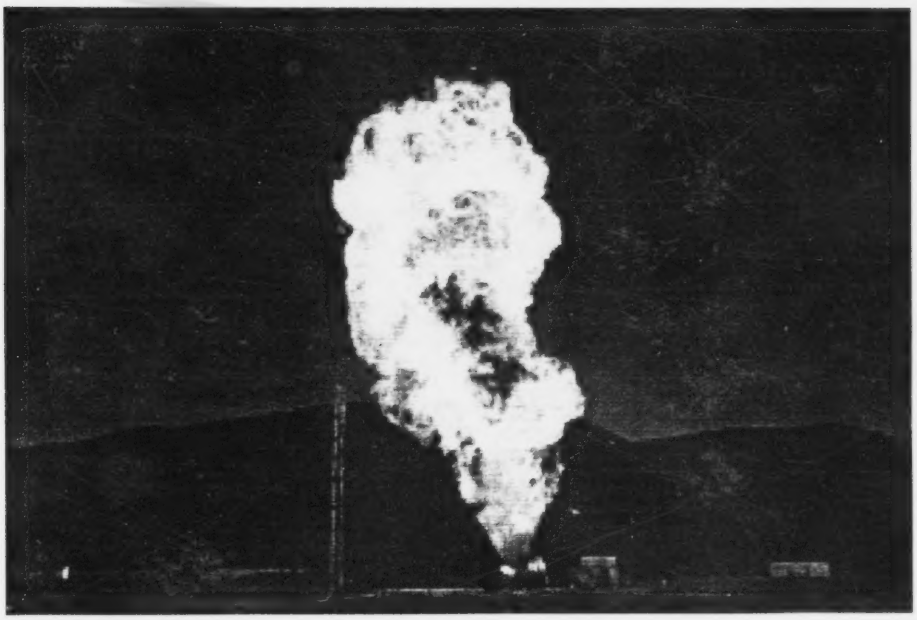
Test 02-1 End Cap

Test 02-2

- 2002 Baseline 30% Blowdown Test, June 19, 2002
- 30% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 4 burners on liquid space (waist burners removed), 2 burners on vapour space
- 22°C, 4 km/h south east wind across tank axis, blue skies
- thin tank

The second test of the 2002 series was identical to the first except with a larger blowdown. It failed earlier (8.7 minutes) than the previous test despite the large blowdown. This is perhaps because blowdown has a little effect on severely heated thin tanks and this test started significantly warmer than Test 02-1.

The failure started as a high, large initial jet that lasted 1.7 seconds before the tank BLEVEd. The high momentum jet caused the tank stands to buckle. When the tank failed the crack travelled circumferentially once it hit the PRV coupling. The tank split in half and the end of the tank rocketed off into the PRV wall. This caused significant damage to the PRV wall. Again there was a long duration fireball.

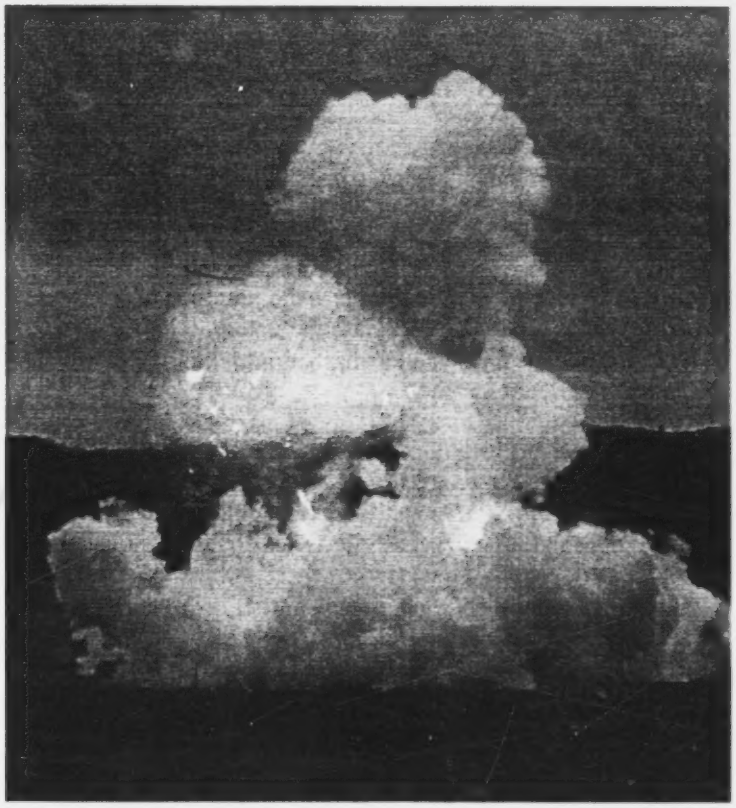


Initial Jet of Test 02-2. (Note Buckled Tank Stand)

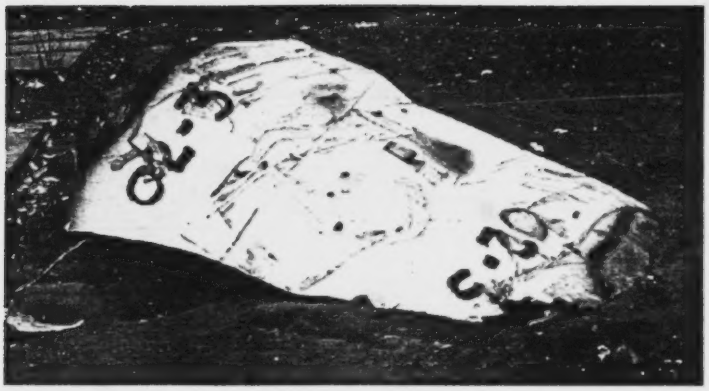
Test 02-3

- Low Fuel Pressure 30% Blowdown Test, June 26, 2002
- 30% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 4 burners on liquid space, 2 burners on vapour space, low fuel pressure
- 22°C, 9 km/h west wind, cloudy
- thin tank

The propane fuel supply was decreased for this test to decrease the heating rate on the vapour space. This improved the survivability of the tank as Test 02-3 lasted 10.8 minutes—over 2 minutes longer than Test 02-2, an other wise identical test. This tank failed as a fast BLEVE. The propane lading did not ignite until 2 seconds after the BLEVE. As a result there was a very low, spread out fire cloud. The tank again broke into three pieces—a flattened cylinder and two end caps.



Late Ignition of Test 02-3 Fireball (Note Localized Flames)

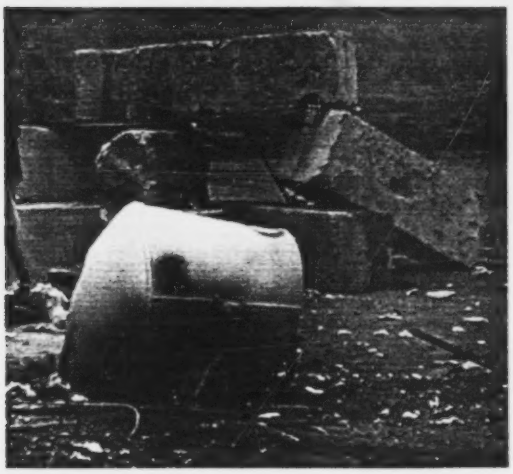


Part of Tank 02-3

Test 02-4

- Low Fuel Pressure 5% Blowdown Test, July 2, 2002
- 5% Blowdown, Set Pressure of 1.9 MPa (gauge)
- 21 mm Nozzle Diameter
- 4 burners on liquid space, 2 burners on vapour space, low fuel pressure
- 27°C, 7 km/h southwest wind, blue skies
- thin tank

This small blowdown test failed at almost the identical time as the previous large blowdown test. Again the tank failed as a fast BLEVE, but this time the propane never ignited. Like in Test 02-2, a tub rocket was formed and smashed into the PRV Wall. The tank broke into three pieces again.



Test 02-4 Rocket and Damage

Test 02-4 Propane Cloud (No Ignition)

Additional Test Data

Input Data

		Vapour	Liquid	Fuel	Min Wall	Initial		
	Blowdown	Burners	Burners	Pressure	Thickness	Temp	Coupling	Nozzle
	(%)			(psi)	(mm)	(°C)	(in)	(mm)
Test 00-1	20	2	12	40	7.7	19	1.5	24
Test 00-2	5	2	12	40	7.7	10	1.5	24
Test 00-3	20	2	8	40	7.7	17	1.5	24
Test 01-1	30	3	10	40	7.7	24	2	21
Test 01-2	5	3	10	40	7.7	13	2	21
Test 01-3	30	3	10	40	7.7	19	2	21
Test 01-4	5	3	10	40	7.7	20	2	21
Test 01-5	45	3	10	40	7.7	20	1.5	21
Test 01-6	5	3	4	40	7.7	18	1.5	21
Test 02-1	5	2	4	40	7.1	11	2	21
Test 02-2	30	2	4	40	7.1	22	2	21
Test 02-3	30	2	4	25	7.1	22	2	21
Test 02-4	5	2	4	25	7.1	27	2	21

Output Data

	Test Time (s)	time to 1st pop (s)	fill (%)	cycles	Tank Pressure (kPag)	Liquid Temp (°C)	Vapour Temp (°C)	Liquid Energy (kJ)	Vapour Energy (kJ)	Total Energy (kJ)
Test 00-1	783	132	0.14	16	1854.5	57.691	125.192	7369	8101	15470
Test 00-2	812	141	0.2	91	1842.1	55.951	111.713	7934	7534	15468
Test 00-3	1032	121	0.17	28	1885.5	53.913	127.455	8032	6085	14117
Test 01-1	911	114	0.173238	9	1863.4	54.456	126.697	9038	7878	16916
Test 01-2	648	146	0.349521	69	1846.4	54.605	67.749	18241	6339	24580
Test 01-3	938	140	0.129545	11	1699.3	55.309	116.18	6521	7181	13702
Test 01-4	746	104	0.210213	82	1894.6	57.399	100.787	11253	7625	18878
Test 01-5	980	129	0.123935	4	1573	49.493	144.93	5986	6545	12531
Test 01-6	601	215	0.491801	38	1881.4	56.237	58.972	26150	5281	31431
Test 02-1	566.6	263.7	0.51	29	1803.4	57.0743	61.1887	27681	5363	33044
Test 02-2	523.4	250.4	0.52	2	1563.3	47.1711	51.8984	24556	4163	28719
Test 02-3	650.9	299.7	0.53	2	1813.1	51.6246	78.8882	26407	4766	31173
Test 02-4	641.2	292.4	0.61	29	1857.8	54.0295	57.1603	29985	4428	34413

	Peak Energy (kJ)	Liquid Mass (kg)	Vapour Mass (kg)	time to peak E (s)	Strat Beta	time to destratify (s)	Wall Temp (°C)	Wall T at 5 min (°C)	time to 427°C (s)	time open valve (s)	% open
Test 00-1	39900	114.3	48.43	168	1.07929	175	740	576	196	362.5	55.7
Test 00-2	40100	175.6	47.6	237	1.01692	245	750	581	186	320.4	47.7
Test 00-3	37600	144.2	39.1	231	1.06027	245	730	491	241	354.8	38.9
Test 01-1	38100	144.1	46.76	171	1.12468	180	710	556	201	455.7	57.2
Test 01-2	40600	290.7	48.36	259	1.02745	270	750	656	175	268.3	53.4
Test 01-3	38400	109.2	45.41	201	1.18004	220	800	625	172	468.6	58.7
Test 01-4	41400	173	49.88	233	1.0105	240	700	554	141	356.4	55.5
Test 01-5	34400	105.9	38.27	126	1.13801	150	770	518	228	596.3	70.1
Test 01-6	41800	406	41.43	286	1.01507	290	730	738	62	175.7	45.5
Test 02-1	42100	425.3	41.2	332	1	450	710	655	135.6	150	49.5
Test 02-2	38900	446.2	34.48	248	1.02857	250	760	688	132.6	171.2	62.7
Test 02-3	39600	443	34.2	299	1.07459	350	730	586	192.5	154	43.8
Test 02-4	41000	483	35	353	1.01456	475	700	583	168.1	110.7	31.7

Appendix D: Analysis Notes

Lading Temperature Calculations

In order to observe some general trends it is desired to discuss the average liquid and average vapour temperatures. To calculate this, it was necessary to go through the lading thermocouple data (48 thermocouples) and determine for each time step, whether each thermocouple was in the vapour or in the liquid. This was accomplished using MATLAB code. The input to the code was the lading temperature and pressure data as well as the information about when the PRV was open or closed.

The program assumed that the pressure in the tank corresponded to the saturation pressure given the temperature at the interface. This is generally accepted in the literature. (Venart et al., 1988) The program compared each recorded temperature to the saturation temperature given the recorded tank pressure. This was done using the propane saturation curve and polynomial curve fit equations, Equations D.1 and D.2. If the temperature was greater than the calculated saturated temperature, the thermocouple was said to be in the vapour and if it was lower, it was in the liquid. Swelling, splashing, and thermal expansion complicated this matter somewhat, and upon initial calculation some thermocouples showed evidence of moving from the liquid to the vapour and back to the liquid several times.

$$P_{sat} = 8.512 \cdot 10^{-4} \cdot T^3 + 0.154 \cdot T^2 + 14.724 \cdot T + 477.517 \qquad \text{(D.1)}$$

$$T_{sat} = 5.492 \cdot 10^{-9} \cdot P^3 - 3.212 \cdot 10^{-5} \cdot P^2 + 8.873 \cdot 10^{-2} \cdot P - 35.247 \qquad \text{(D.2)}$$

The program was adjusted using several correction routines and checks:

- A range of 1°C was used as a transition range. For example, a thermocouple in the liquid was not considered to move into the vapour region until its temperature was 1°C greater than the saturation temperature given the tank pressure.
- The fill level was not allowed to decrease while the PRV was closed.
- Typically when a thermocouple moves from the liquid to the vapour, the temperature sees a sudden rise in temperature. If a change was sensed, the program checked the previous two and the next two time steps to ensure the right trends were being predicted.
- If a thermocouple moved into the vapour region, all the thermocouples above that thermocouple had to be in the vapour. An error was given if this wasn't the case.
- While a thermocouple was allowed to move back and forth from the vapour to the liquid, only one thermocouple on each bundle was allowed to do this at a time. Once a lower thermocouple made a transition from liquid to vapour, the thermocouple immediately above it was considered to be in the vapour for the remainder of the test.

The program outputted the average liquid and vapour temperatures, with each thermocouple given an equal weight.

Mass Flow Calculations

The mass flow calculations presented below assumes a single phase, choked and isentropic flow at the nozzle, and treat the superheated propane vapour as an ideal gas. An EES (Engineering Equation Solver--F-Chart Software) program used the built-in propane data to perform the calculations. The program reads in the nozzle temperature and pressure for each time step (10 readings per second) and outputs the accumulated mass flow with time. The following steps were employed:

- Assuming a specific heat ratio ($k=c_p/c_v$) of 1.1 and using Equation D.3 (an ideal gas, compressible flow relationship) for a converging nozzle, the pressure ratio between the throat pressure and the stagnation pressure was calculated to be 0.59.

$$\frac{P_{throat}}{P_{stag}} = \left[\frac{2}{k+1}\right]^{\frac{k}{k-1}} \tag{D.3}$$

- The point where the pressure and temperature measurements were made was assumed to be a stagnation point and the pressure ratio calculated above was used to determine the pressure in the nozzle (throat). This assumption is reasonable because the cross sectional area of the pipe was over 14 times bigger than the area of the nozzle for the 2001 tests and approximately 11 times bigger in the 2000 tests.
- For a check, the real value of the specific heat ratio was calculated given the measured pressure and temperature in the nozzle. The value for k was in the range of 1.07 to 1.13 for a practical range of nozzle temperatures.
- The pressure data was used to determine when the valve was open and when it was closed. This was possible because the pressure takes a dramatic change when the valve opens and closes. The PRV position data recorded by the data acquisition system was found to be inadequate because it recorded when the signal was sent to the valve and not when the valve actually opened and closed.
- Using the tabulated propane data in EES, the enthalpy and entropy were calculated for the stagnation point using the measured temperature and pressure.

$$h_{stag}=h(T,P) \tag{D.4}$$

$$s_{stag}=s(T,P) \tag{D.5}$$

- Assuming isentropic expansion, the enthalpy was calculated at the throat, given P_{throat} and the entropy, again using the tabulated propane data in EES.

$$h_{throat}=h(P_{throat},s_{stag}) \tag{D.6}$$

- Using the enthalpy at the stagnation point and at the nozzle, the velocity at the nozzle was determined using Equation D.7.

$$h_{throat} + \frac{(v_{throat})^2}{2} = h_{stag} \tag{D.7}$$

- Using the tabulated density, the calculated velocity, measured nozzle diameter, and an assumed nozzle discharge coefficient of C_D=99%, the mass flow rate was calculated.

$$\dot{m} = C_D \cdot \rho \cdot v \cdot A \tag{D.8}$$

- The mass flow rate was integrated over time to find the total mass that had exited the tank. The amount of mass that had exited the tank at any given time was determined by Equation D.9.

$$m_{exit} = \int_0 \dot{m} \cdot dt \tag{D.9}$$

Tank Energy Calculations

An EES program was written that read in the average liquid temperature, the average vapour temperature, and the tank pressure for each time step. It output the mass and available energy stored in each phase. The following steps were employed:

- Given the temperature and pressure input, the initial specific internal energy and entropy were determined using the tabulated values, according to Equations D.10 and D.11.

$$u_{1,l} = u(T_{1,l}, P_1); u_{1,v} = u(T_{1,v}, P_1) \tag{D.10}$$

$$s_{1,l} = s(T_{1,l}, P_1); s_{1,v} = u(T_{1,v}, P_1) \tag{D.11}$$

- Assuming isentropic expansion to atmospheric pressure (P_2=101.325kPa), the internal energy and entropy were determined for the final state according to Equations D.12 and D.13.

$$s_{2,l} = s_{1,l}; s_{2,v} = s_{1,v} \tag{D.12}$$

$$u_{2,l} = u(s_{2,l}, P_2); u_{2,v} = u(s_{2,v}, P_2) \tag{D.13}$$

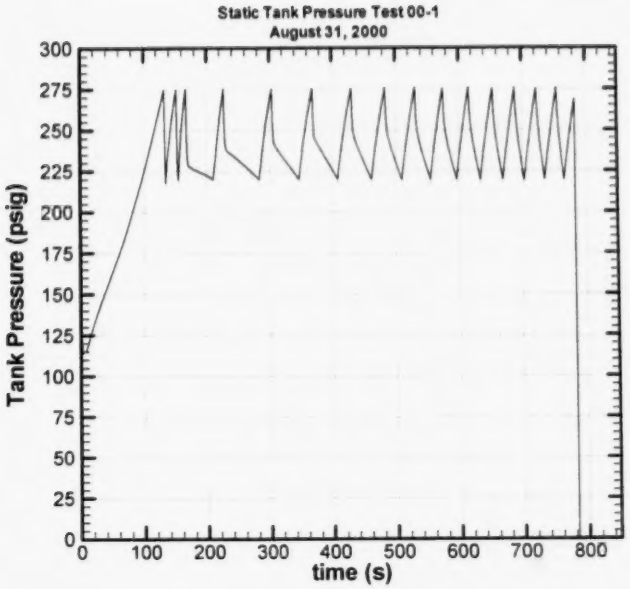
- The mass in each phase was calculated by determining the density using the EES values and the volume given the fill level.
- The isentropic expansion energy in each phase was calculated as the change in internal energy between the two states multiplied by the mass in that phase, according to Equation D.14.

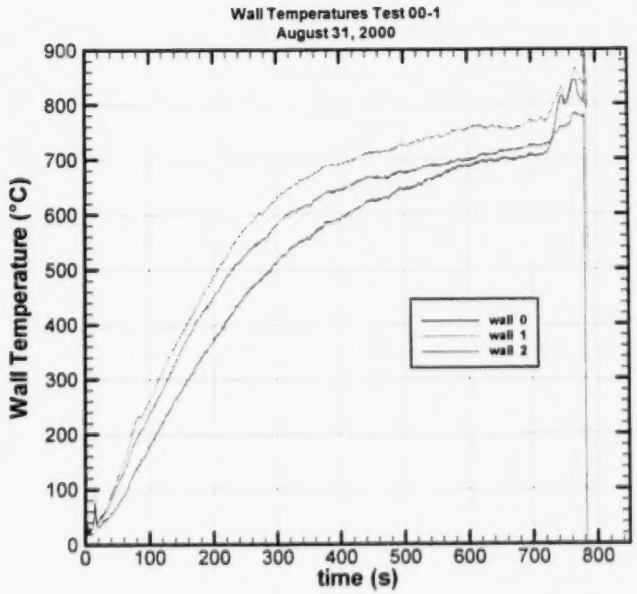
$$E_l = m_l(u_{2,l} - u_{1,l}); E_v = m_v(u_{2,v} - u_{1,v}) \tag{D.14}$$

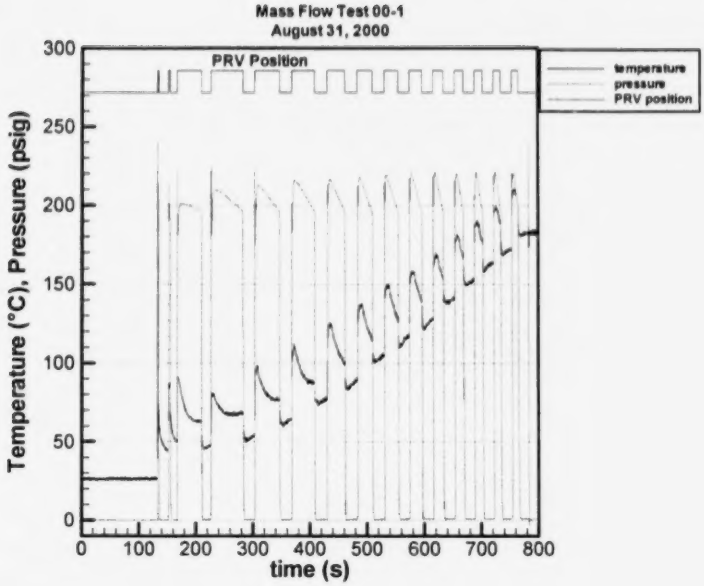
Appendix E: Additional Data Plots

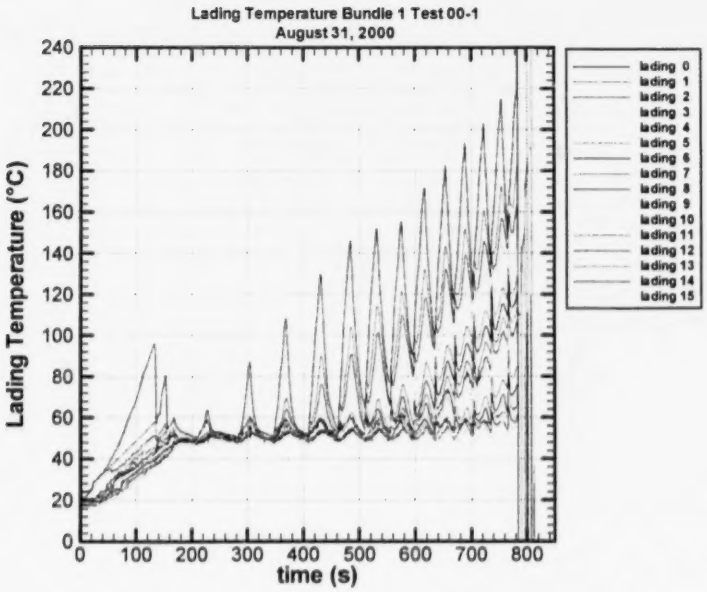
The following plots are presented below for each of the thirteen tests:

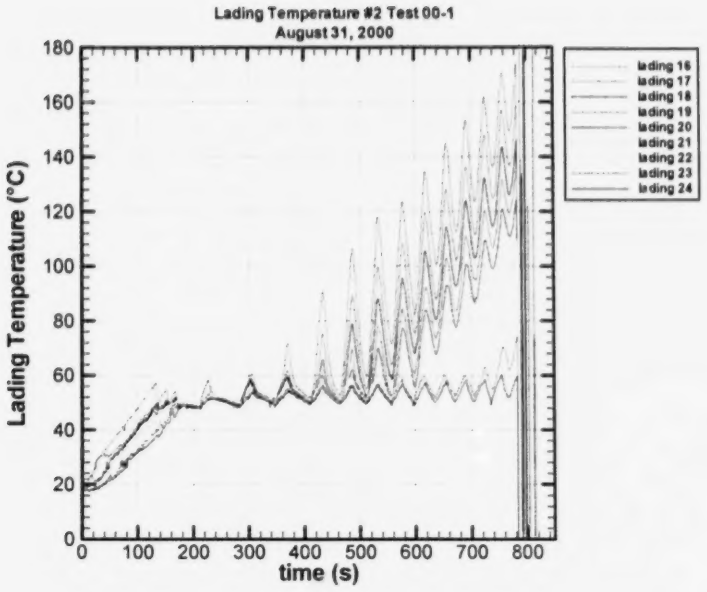
- Tank Pressure
- Wall Temperature
- PRV Mass Flow Data
- Lading Temperature Data (Bundle 1)
- Lading Temperature Data (Bundle 2 or 3)
- Lading Temperature Data (Bundle 4 or 5)
- Beta Analysis/Average Lading Temperature
- Tank Energy

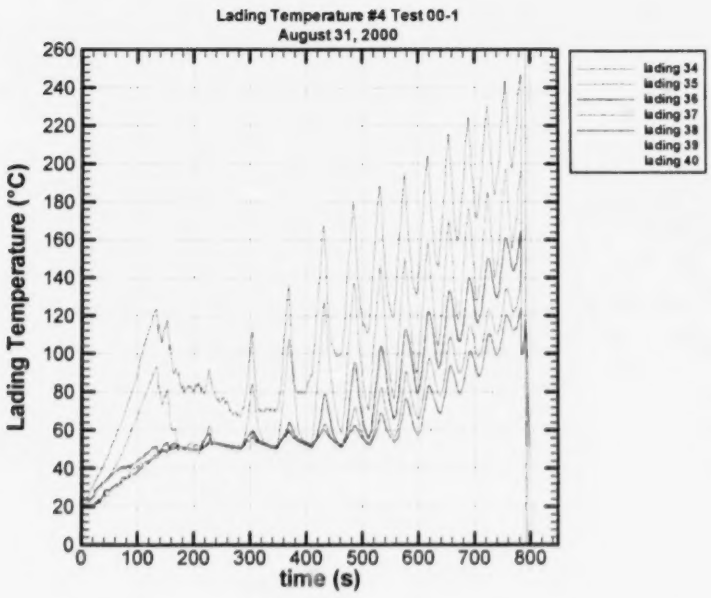

Static Tank Pressure Test 00-1
August 31, 2000
Tank Pressure (psig)
time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
0
100
200
300
400
500
600
700
800

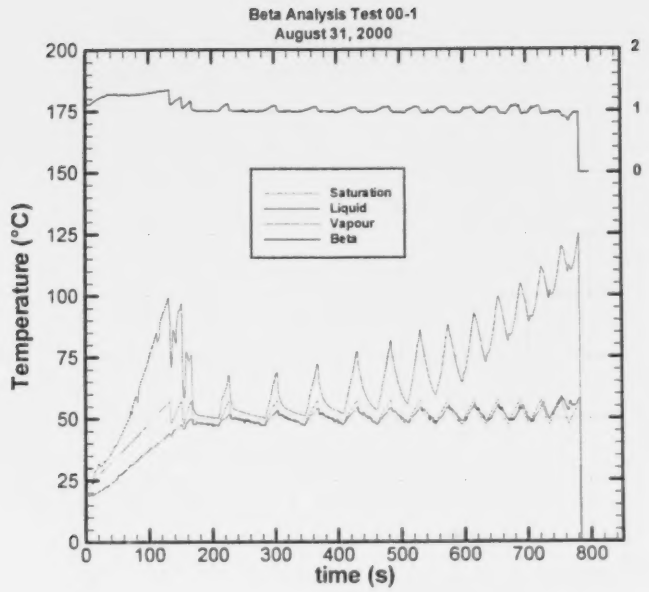

Wall Temperatures Test 00-1
August 31, 2000
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
0
100
200
300
400
500
600
700
800
900
0
100
200
300
400
500
600
700
800

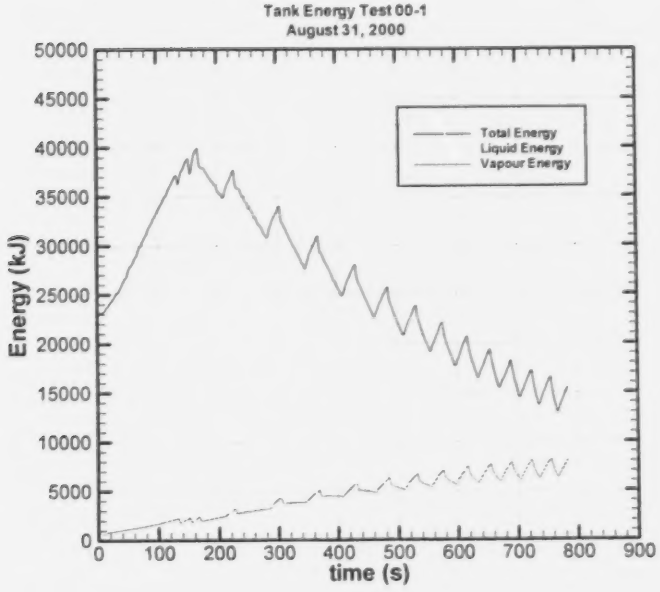

Mass Flow Test 00-1
August 31, 2000
PRV Position
temperature
pressure
PRV position
Temperature (°C), Pressure (psig)
time (s)
0
50
100
150
200
250
300
0
100
200
300
400
500
600
700
800

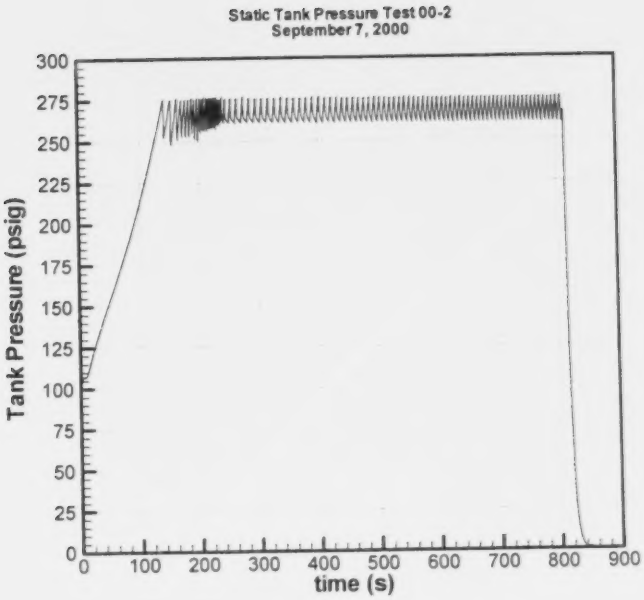

Lading Temperature Bundle 1 Test 00-1
August 31, 2000
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
Lading Temperature (°C)
time (s)
0
20
40
60
80
100
120
140
160
180
200
220
240
0
100
200
300
400
500
600
700
800

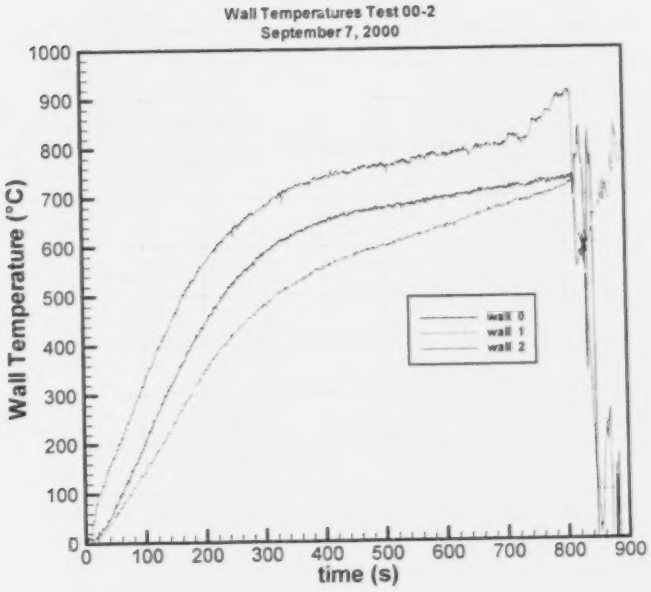

Lading Temperature #2 Test 00-1
August 31, 2000
Lading Temperature (°C)
time (s)
lading 16
lading 17
lading 18
lading 19
lading 20
lading 21
lading 22
lading 23
lading 24

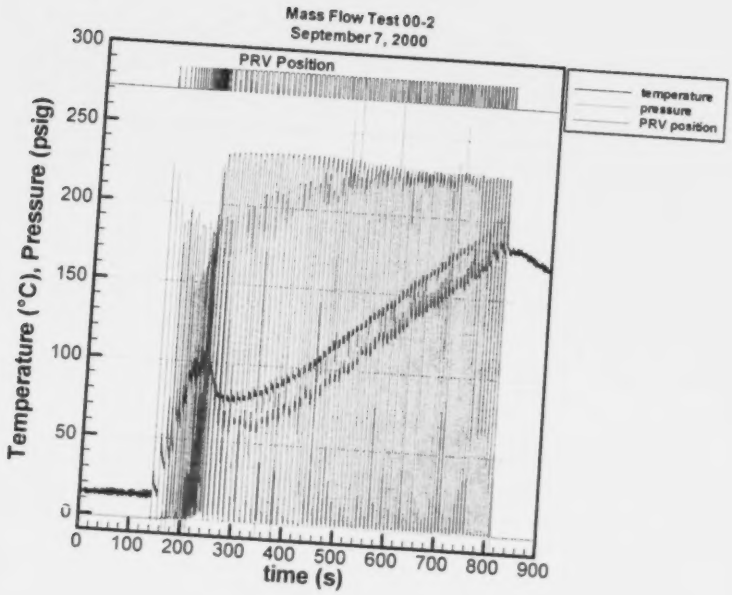

Lading Temperature #4 Test 00-1
August 31, 2000
Lading Temperature (°C)
time (s)
lading 34
lading 35
lading 36
lading 37
lading 38
lading 39
lading 40

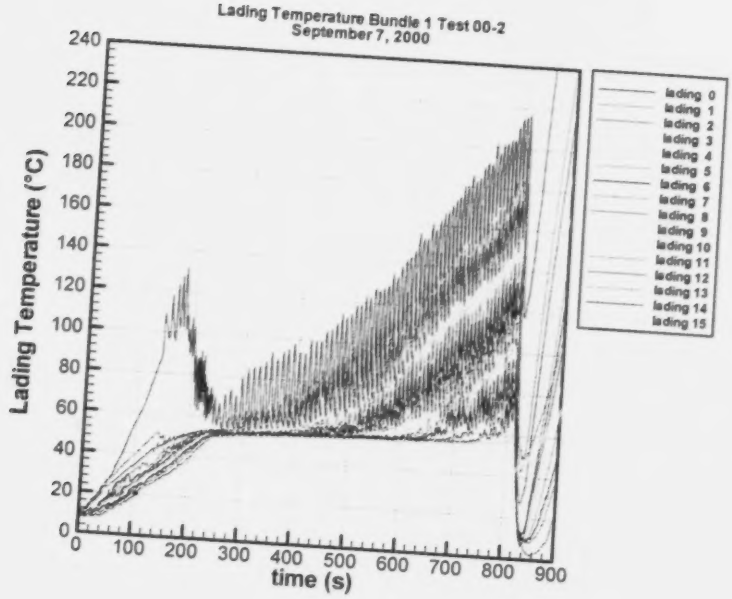

Beta Analysis Test 00-1
August 31, 2000
Temperature (°C)
time (s)
Saturation
Liquid
Vapour
Beta
200
175
150
125
100
75
50
25
0
2
1
0
0
100
200
300
400
500
600
700
800

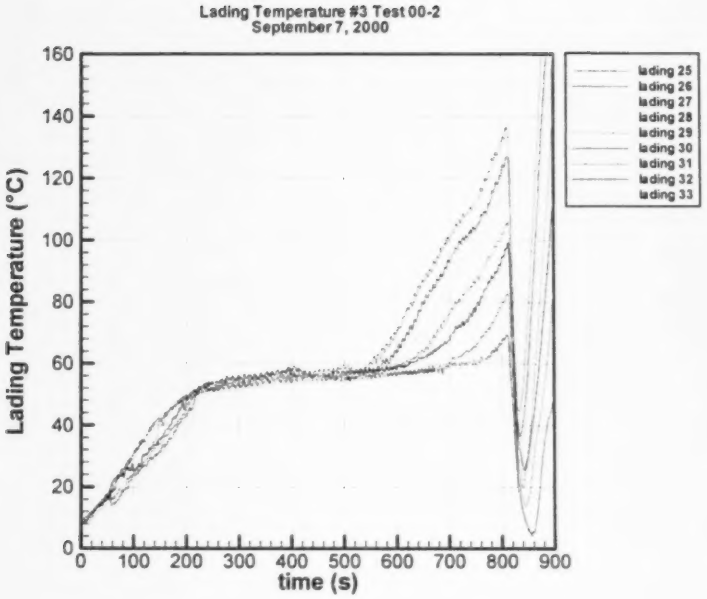

Tank Energy Test 00-1
August 31, 2000
Energy (kJ)
time (s)
Total Energy
Liquid Energy
Vapour Energy
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
800
900

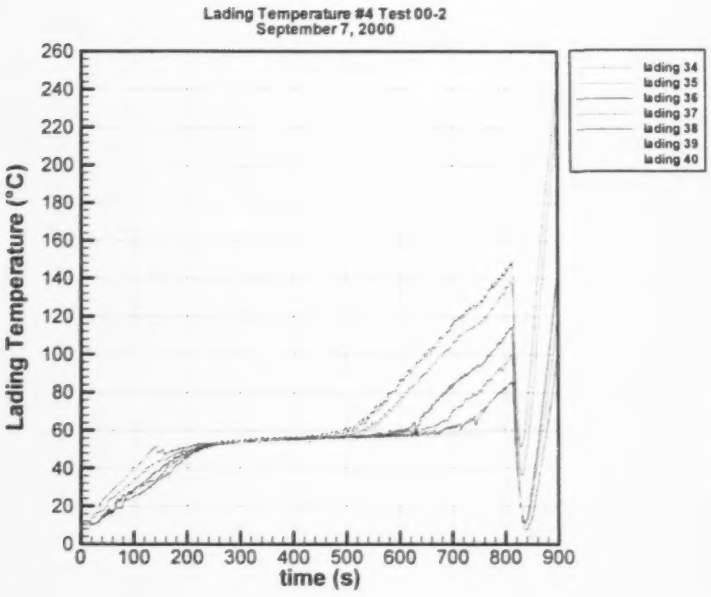

Static Tank Pressure Test 00-2
September 7, 2000
Tank Pressure (psig)
time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
0
100
200
300
400
500
600
700
800
900

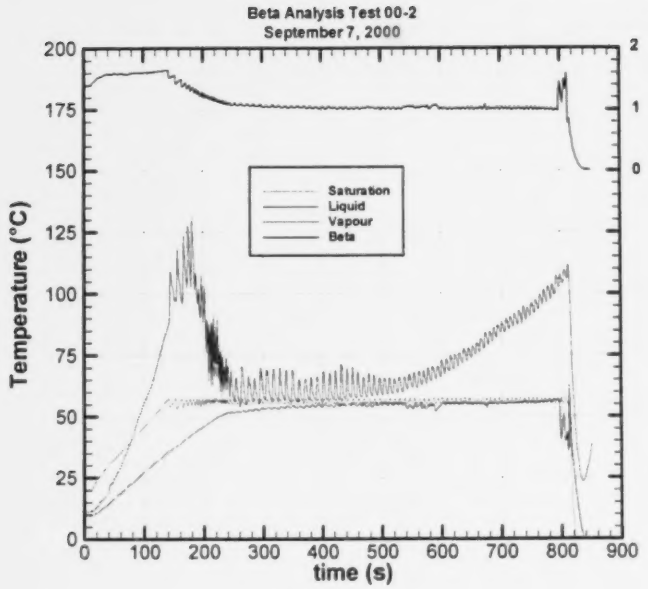

Wall Temperatures Test 00-2
September 7, 2000
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
0
100
200
300
400
500
600
700
800
900
1000
0
100
200
300
400
500
600
700
800
900

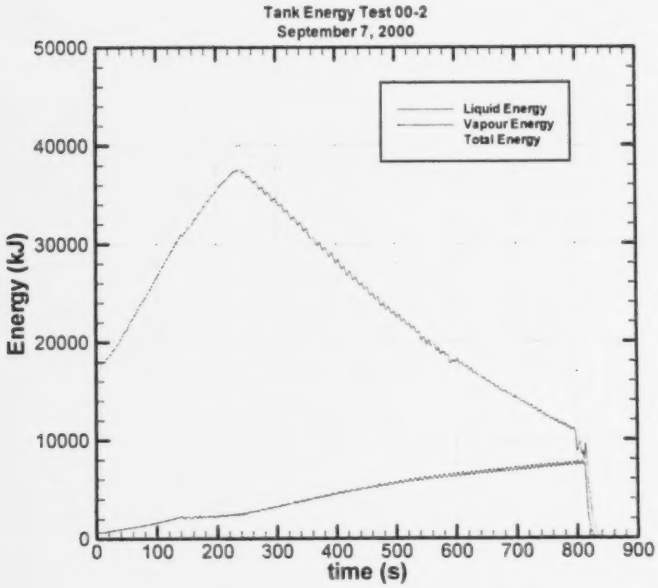

Mass Flow Test 00-2
September 7, 2000
PRV Position
temperature
pressure
PRV position
Temperature (°C), Pressure (psig)
time (s)
0
50
100
150
200
250
300
0
100
200
300
400
500
600
700
800
900

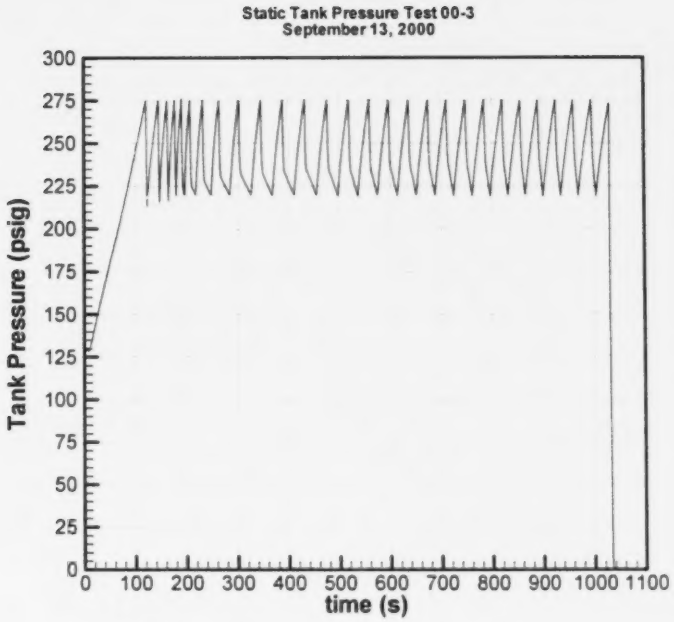

Lading Temperature Bundle 1 Test 00-2
September 7, 2000
Lading 0
Lading 1
Lading 2
Lading 3
Lading 4
Lading 5
Lading 6
Lading 7
Lading 8
Lading 9
Lading 10
Lading 11
Lading 12
Lading 13
Lading 14
Lading 15
Lading Temperature (°C)
time (s)
0
20
40
60
80
100
120
140
160
180
200
220
240
0
100
200
300
400
500
600
700
800
900

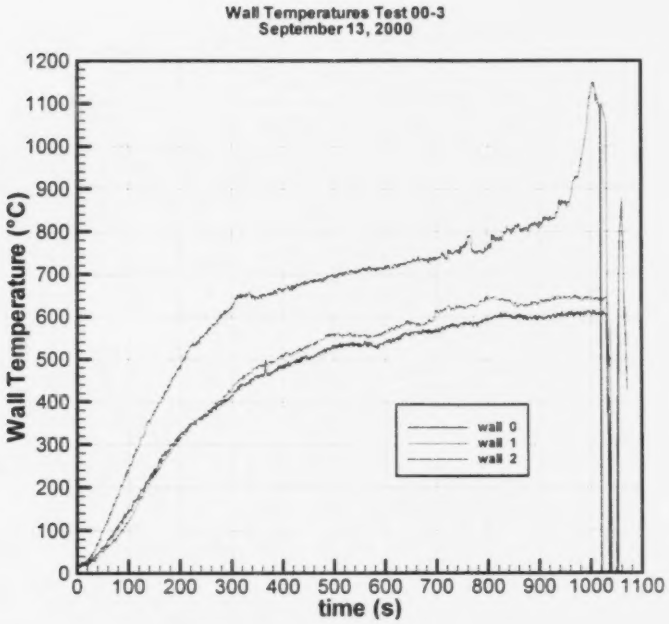

Lading Temperature #3 Test 00-2
September 7, 2000
Lading Temperature (°C)
time (s)
lading 25
lading 26
lading 27
lading 28
lading 29
lading 30
lading 31
lading 32
lading 33

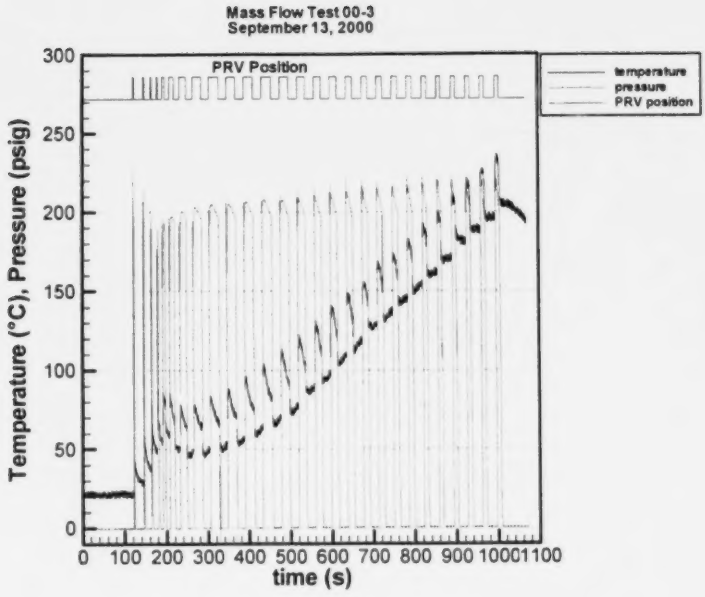

Lading Temperature #4 Test 00-2
September 7, 2000
Lading Temperature (°C)
time (s)
lading 34
lading 35
lading 36
lading 37
lading 38
lading 39
lading 40

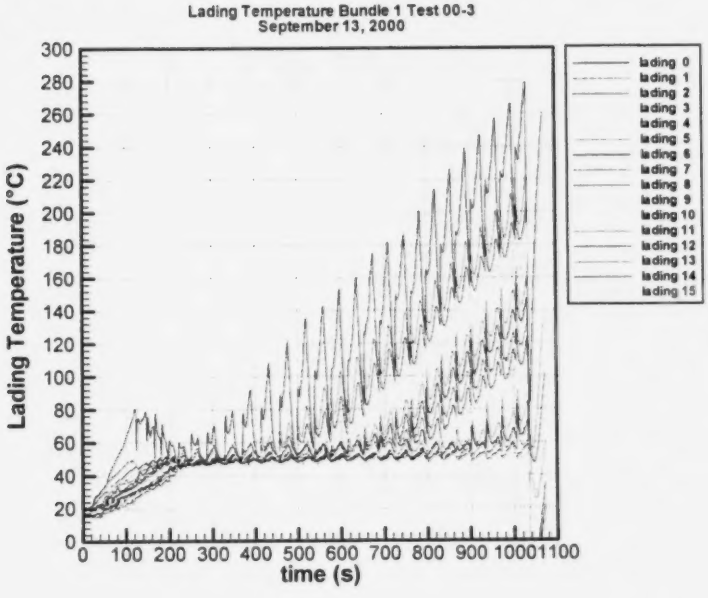

Beta Analysis Test 00-2
September 7, 2000
Temperature (°C)
time (s)
Saturation
Liquid
Vapour
Beta
0
25
50
75
100
125
150
175
200
0
100
200
300
400
500
600
700
800
900
0
1
2

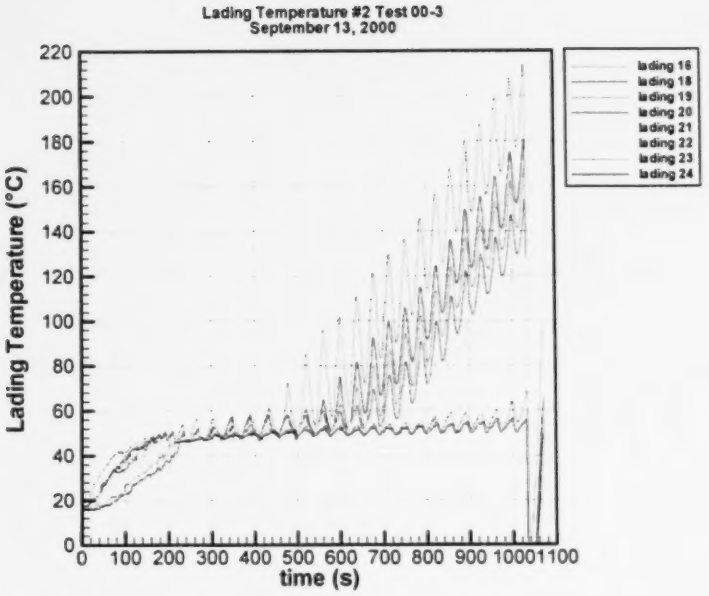

Tank Energy Test 00-2
September 7, 2000
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
0
10000
20000
30000
40000
50000
0
100
200
300
400
500
600
700
800
900

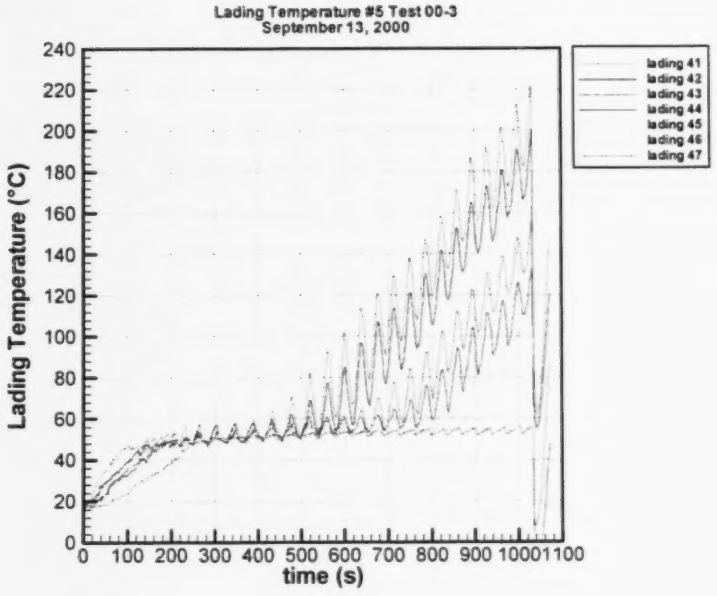

Static Tank Pressure Test 00-3
September 13, 2000
Tank Pressure (psig)
time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
0
100
200
300
400
500
600
700
800
900
1000
1100

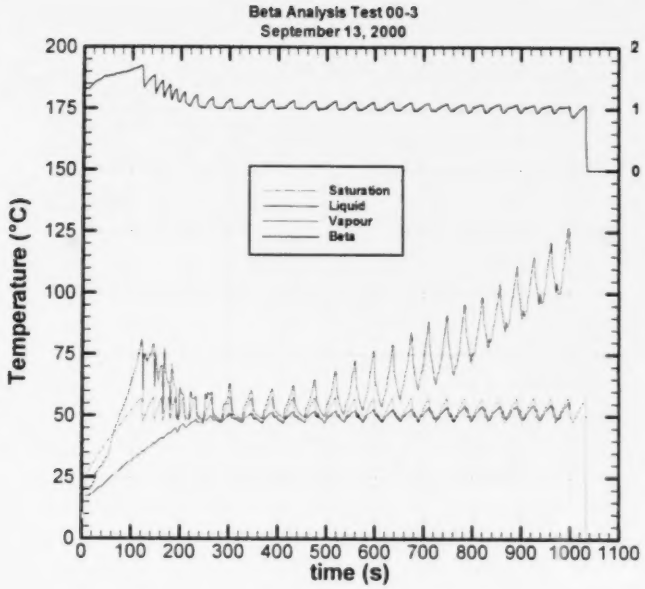

Wall Temperatures Test 00-3
September 13, 2000
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
0
100
200
300
400
500
600
700
800
900
1000
1100
1200

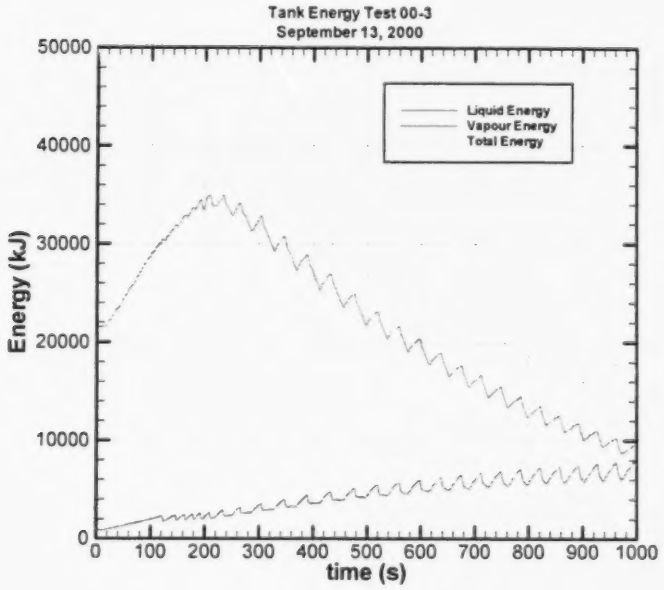

Mass Flow Test 00-3
September 13, 2000
PRV Position
temperature
pressure
PRV position
Temperature (°C), Pressure (psig)
time (s)
0
50
100
150
200
250
300
0 100 200 300 400 500 600 700 800 900 1000 1100

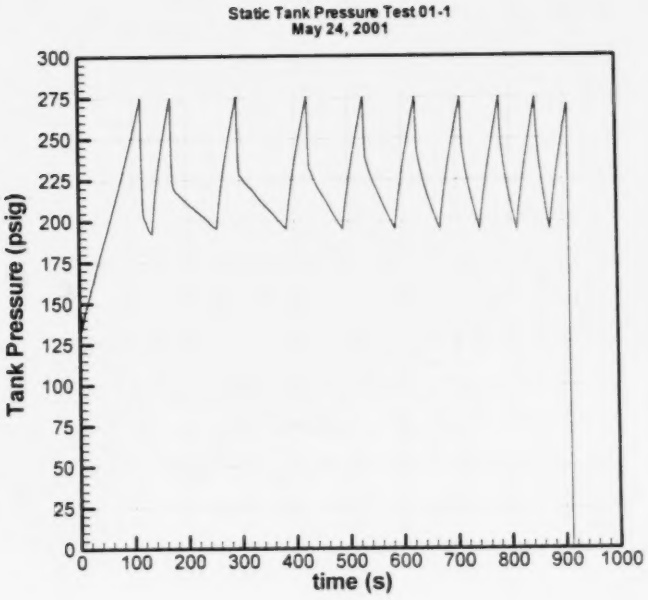

Lading Temperature Bundle 1 Test 00-3
September 13, 2000
Lading Temperature (°C)
time (s)
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
0 100 200 300 400 500 600 700 800 900 1000 1100

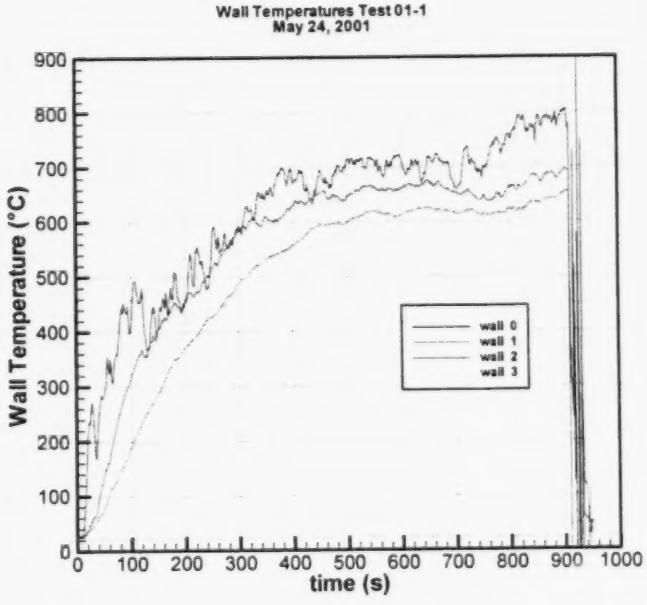

Lading Temperature #2 Test 00-3
September 13, 2000
Lading Temperature (°C)
time (s)
lading 16
lading 18
lading 19
lading 20
lading 21
lading 22
lading 23
lading 24

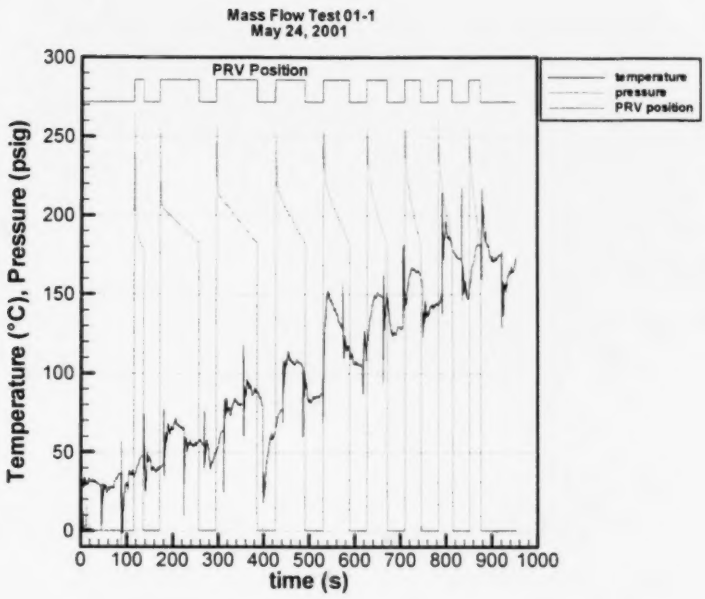

Lading Temperature #5 Test 00-3
September 13, 2000
Lading Temperature (°C)
time (s)
lading 41
lading 42
lading 43
lading 44
lading 45
lading 46
lading 47

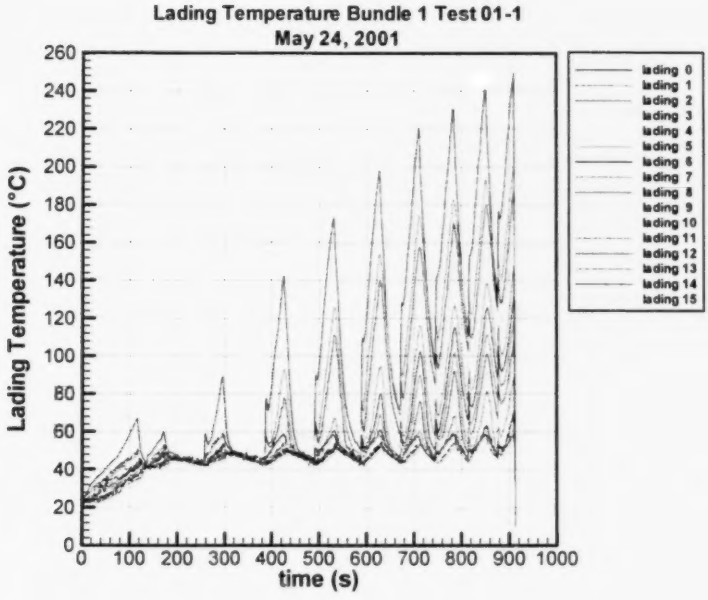

Beta Analysis Test 00-3
September 13, 2000
Temperature (°C)
time (s)
Saturation
Liquid
Vapour
Beta
200
175
150
125
100
75
50
25
0
2
1
0
0
100
200
300
400
500
600
700
800
900
1000
1100

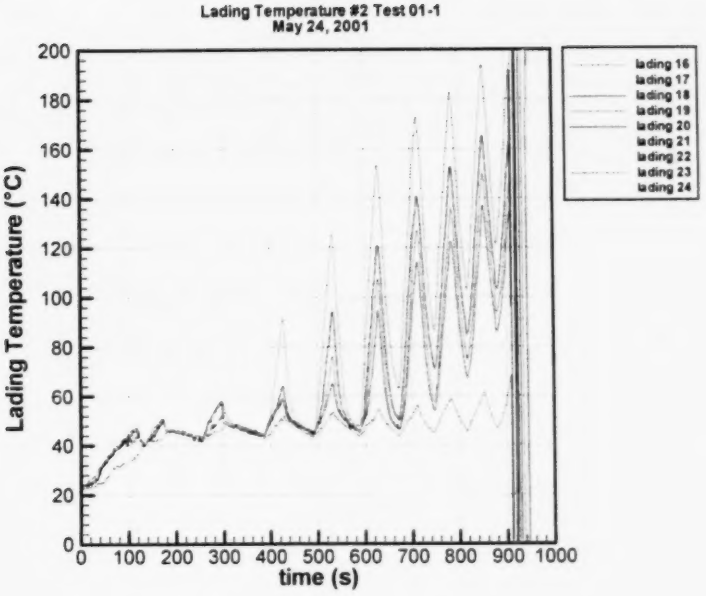

Tank Energy Test 00-3
September 13, 2000
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700
800
900
1000

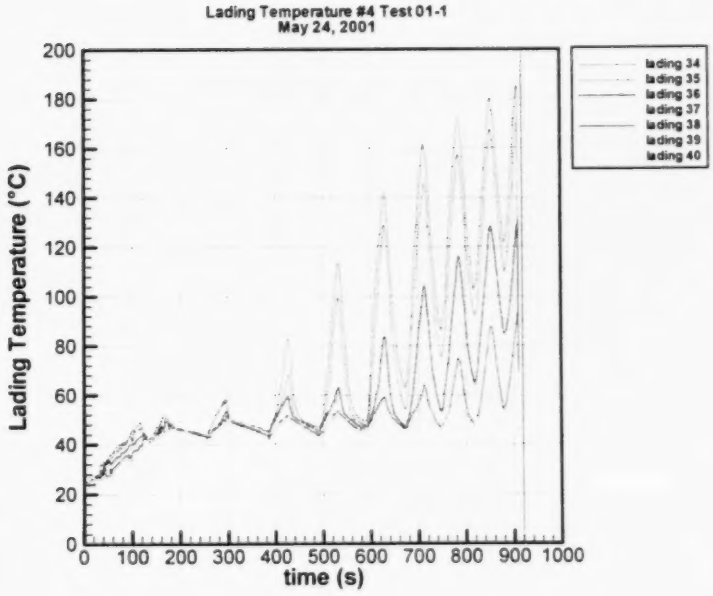

Static Tank Pressure Test 01-1
May 24, 2001
Tank Pressure (psig)
time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
0
100
200
300
400
500
600
700
800
900
1000

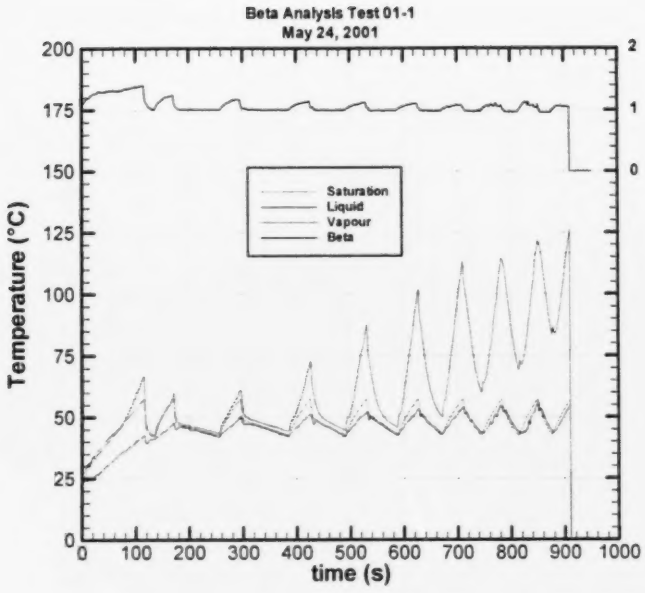

Wall Temperatures Test 01-1
May 24, 2001
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
wall 3
0
100
200
300
400
500
600
700
800
900
1000

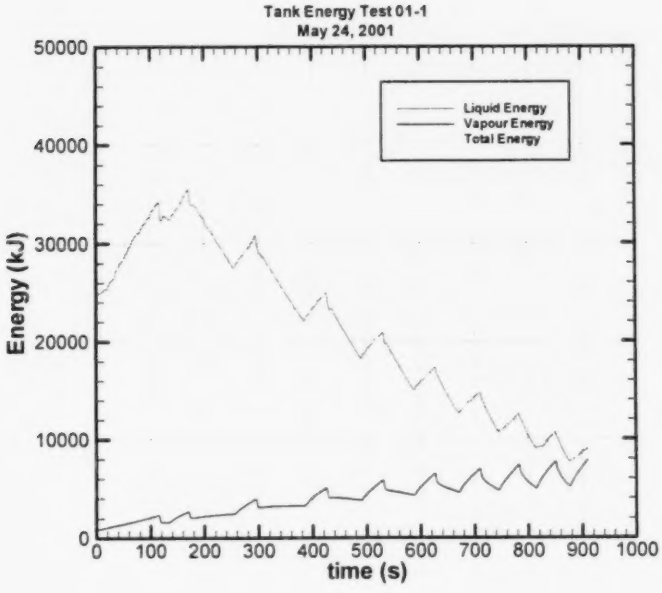

Mass Flow Test 01-1
May 24, 2001
PRV Position
temperature
pressure
PRV position
Temperature (°C), Pressure (psig)
time (s)
0
50
100
150
200
250
300
0 100 200 300 400 500 600 700 800 900 1000

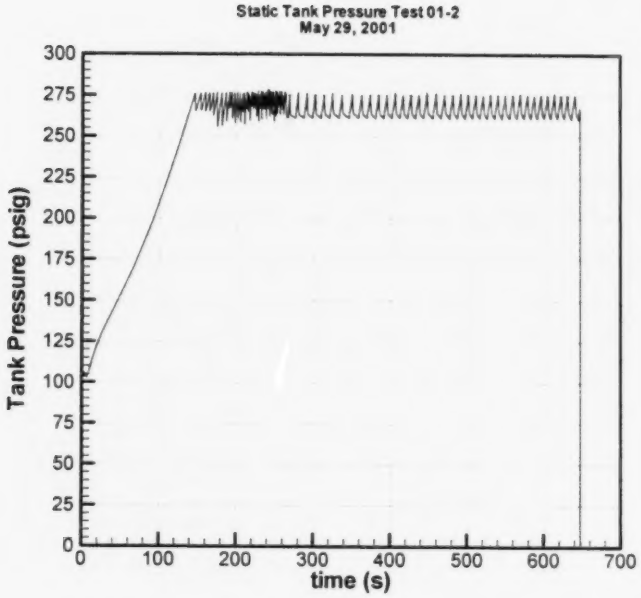

Lading Temperature Bundle 1 Test 01-1
May 24, 2001
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
Lading Temperature (°C)
time (s)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
0 100 200 300 400 500 600 700 800 900 1000

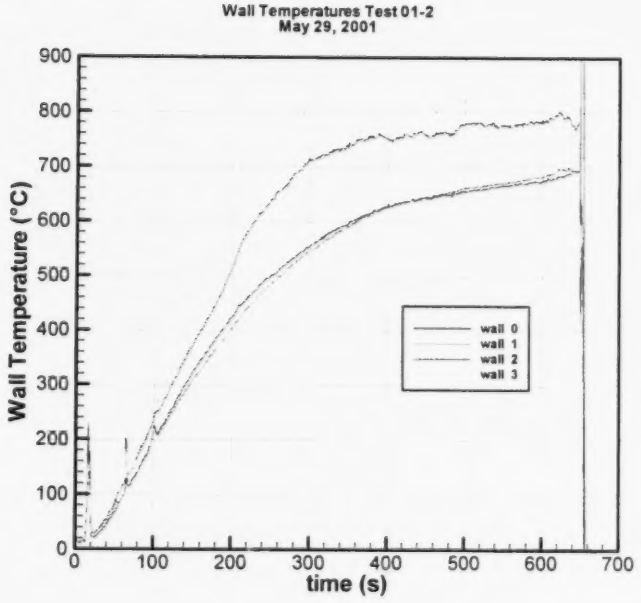

Lading Temperature #2 Test 01-1
May 24, 2001
Lading Temperature (°C)
time (s)
lading 16
lading 17
lading 18
lading 19
lading 20
lading 21
lading 22
lading 23
lading 24

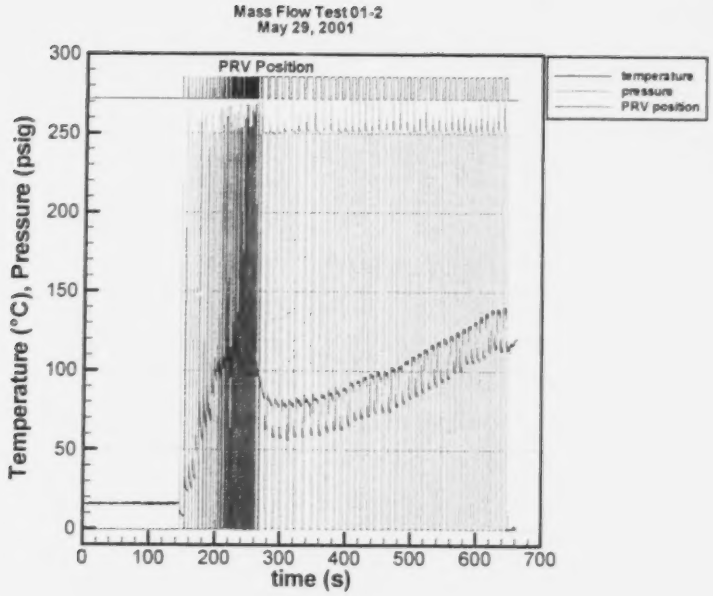

Lading Temperature #4 Test 01-1
May 24, 2001
Lading Temperature (°C)
time (s)
lading 34
lading 35
lading 36
lading 37
lading 38
lading 39
lading 40

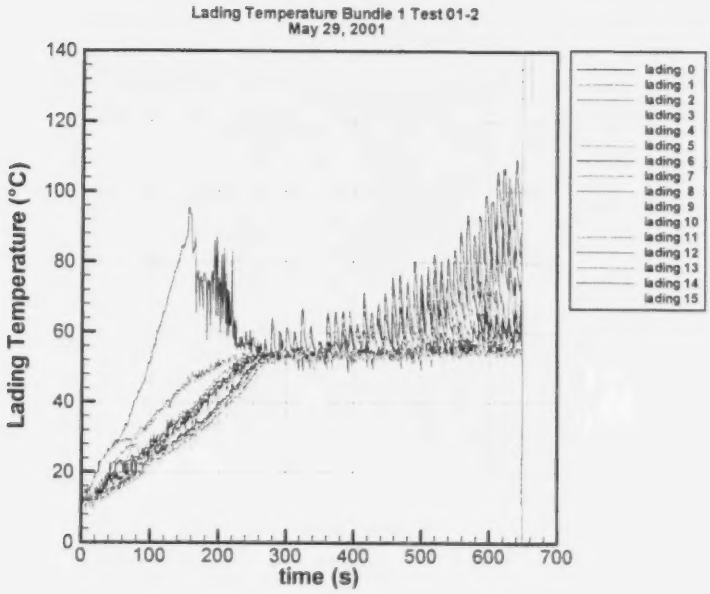

Beta Analysis Test 01-1
May 24, 2001
Temperature (°C)
time (s)
Saturation
Liquid
Vapour
Beta
0
25
50
75
100
125
150
175
200
0
100
200
300
400
500
600
700
800
900
1000
0
1
2

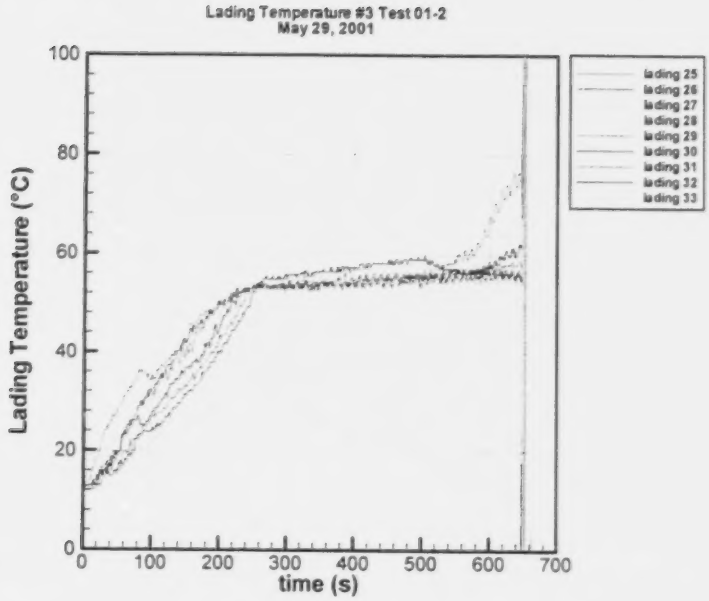

Tank Energy Test 01-1
May 24, 2001
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
0
10000
20000
30000
40000
50000
0
100
200
300
400
500
600
700
800
900
1000

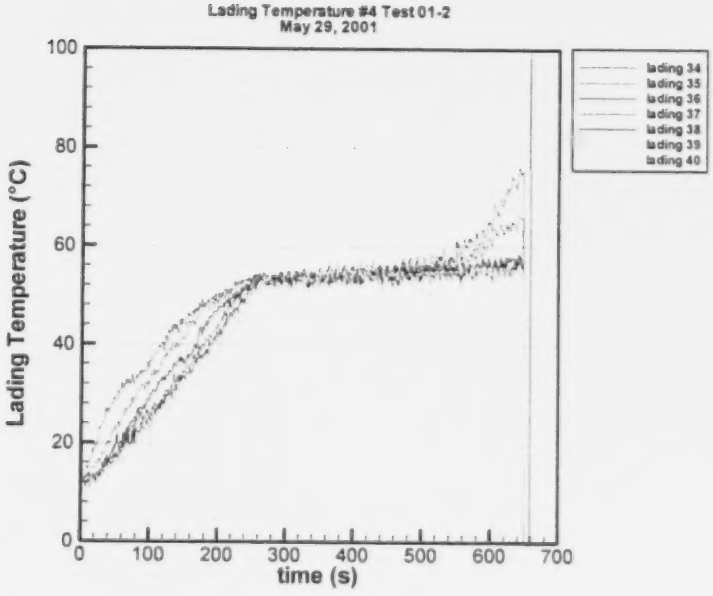

Static Tank Pressure Test 01-2
May 29, 2001
Tank Pressure (psig)
time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
0
100
200
300
400
500
600
700

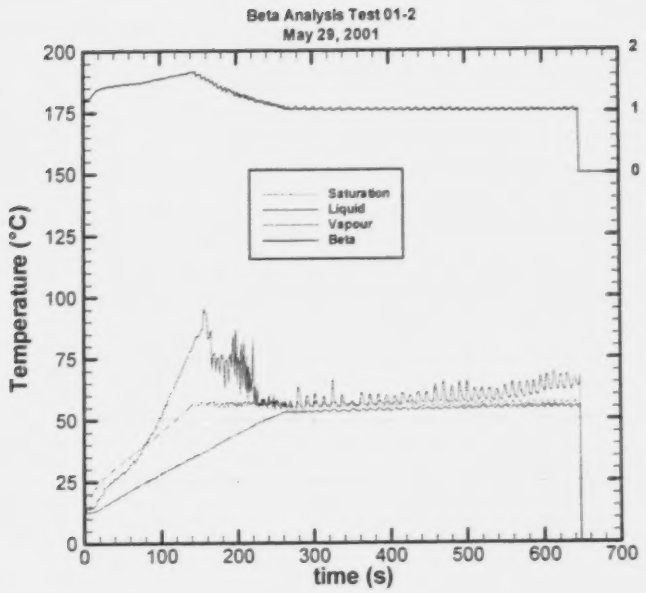

Wall Temperatures Test 01-2
May 29, 2001
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
wall 3
0
100
200
300
400
500
600
700
800
900
0
100
200
300
400
500
600
700

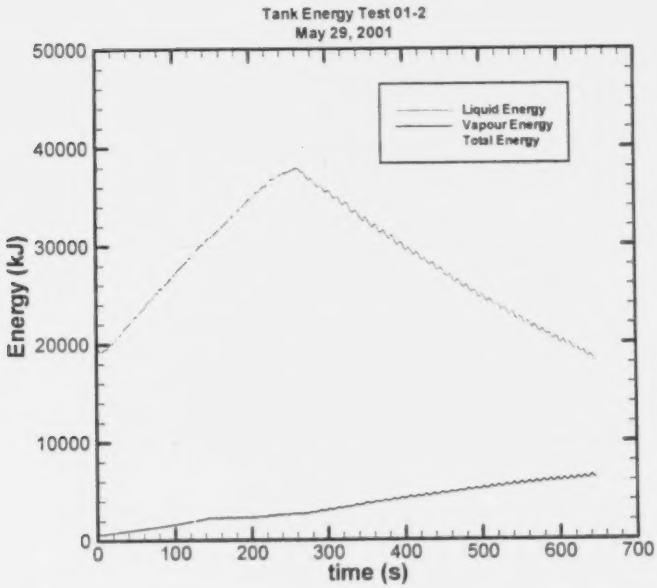

Mass Flow Test 01-2
May 29, 2001
PRV Position
temperature
pressure
PRV position
Temperature (°C), Pressure (psig)
time (s)
0
50
100
150
200
250
300
0
100
200
300
400
500
600
700

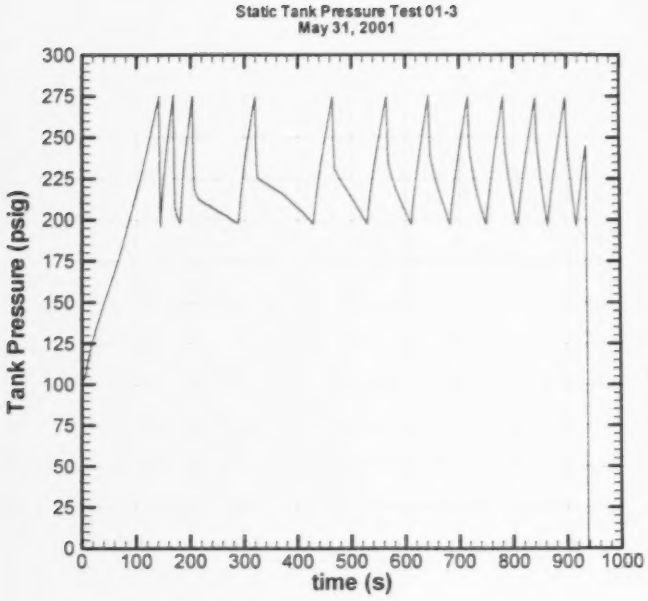

Lading Temperature Bundle 1 Test 01-2
May 29, 2001
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
Lading Temperature (°C)
time (s)
0
20
40
60
80
100
120
140
0
100
200
300
400
500
600
700

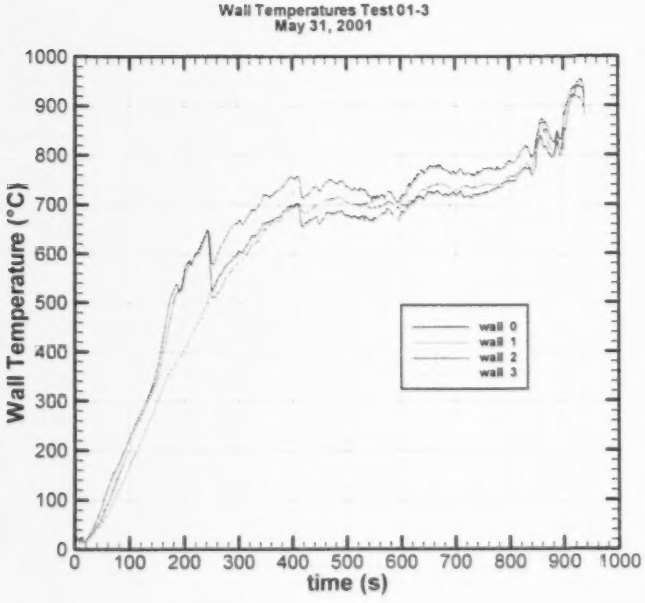

Lading Temperature #3 Test 01-2
May 29, 2001
Lading Temperature (°C)
time (s)
lading 25
lading 26
lading 27
lading 28
lading 29
lading 30
lading 31
lading 32
lading 33

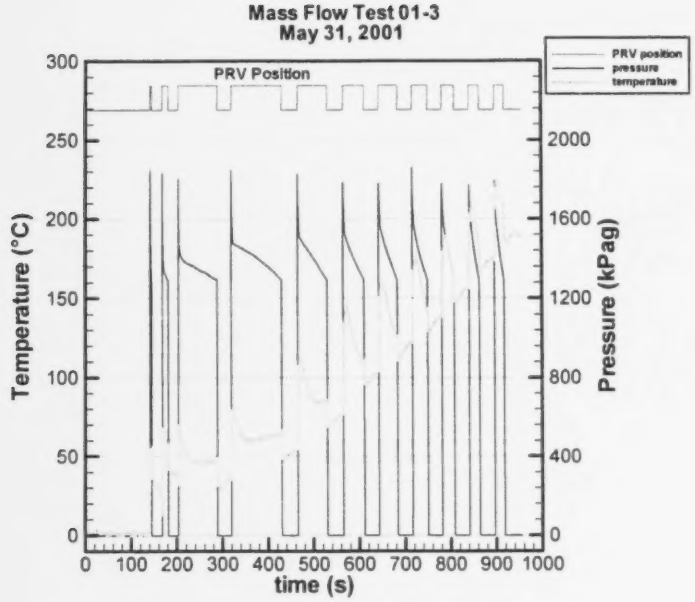

Lading Temperature #4 Test 01-2
May 29, 2001
Lading Temperature (°C)
time (s)
lading 34
lading 35
lading 36
lading 37
lading 38
lading 39
lading 40

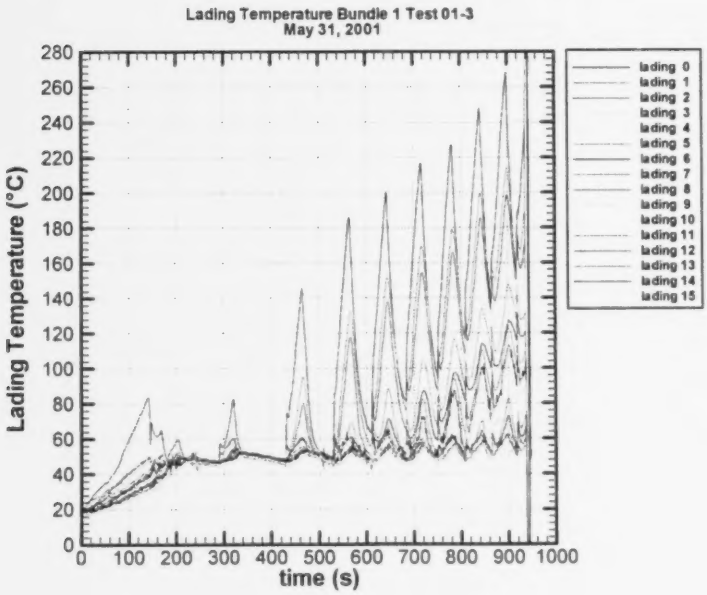

Beta Analysis Test 01-2
May 29, 2001
Temperature (°C)
time (s)
Saturation
Liquid
Vapour
Beta
200
175
150
125
100
75
50
25
0
2
1
0
0
100
200
300
400
500
600
700

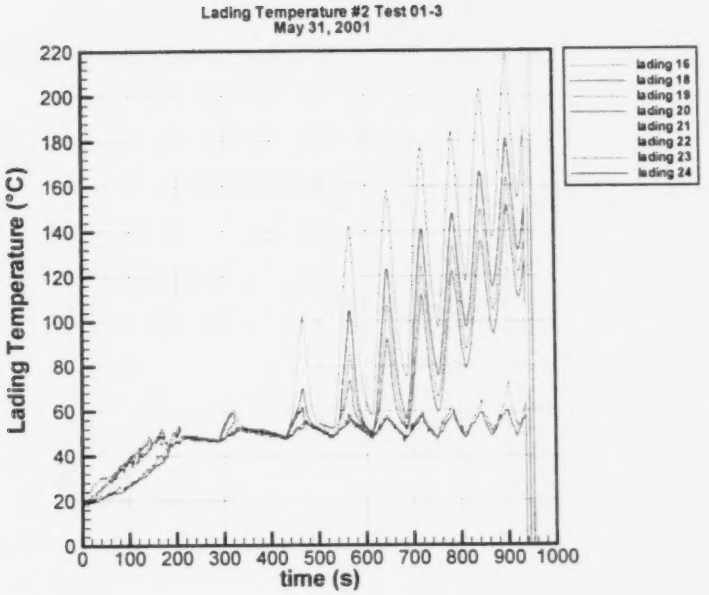

Tank Energy Test 01-2
May 29, 2001
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700

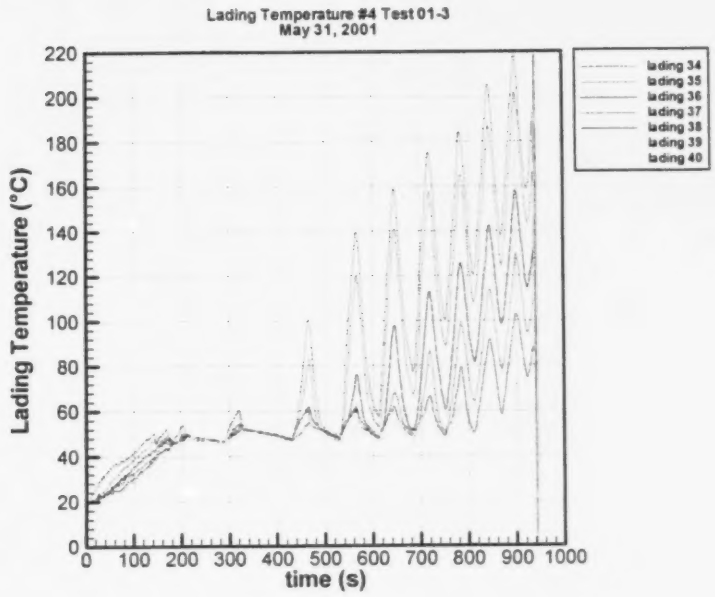

Static Tank Pressure Test 01-3
May 31, 2001
Tank Pressure (psig)
time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
0
100
200
300
400
500
600
700
800
900
1000

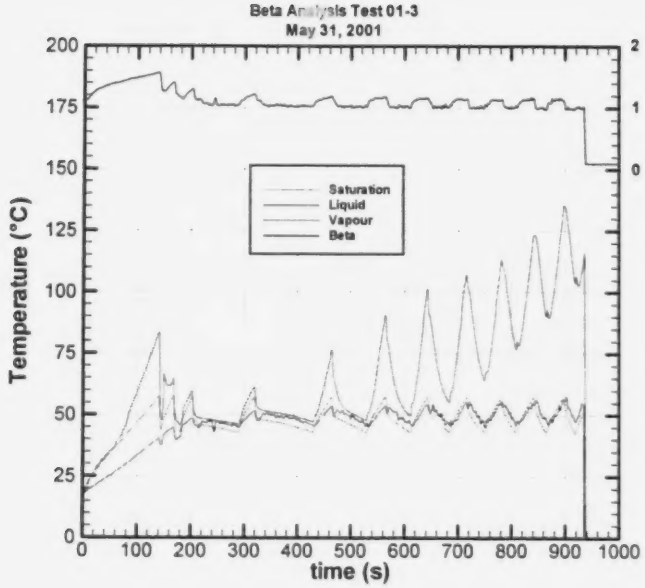

Wall Temperatures Test 01-3
May 31, 2001
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
wall 3
0
100
200
300
400
500
600
700
800
900
1000

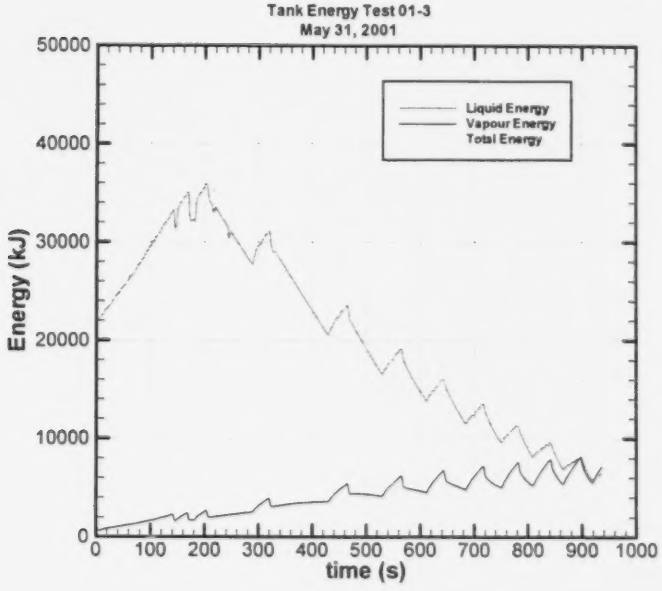

Mass Flow Test 01-3
May 31, 2001
PRV Position
PRV position
pressure
temperature
Temperature (°C)
Pressure (kPag)
time (s)
0
50
100
150
200
250
300
0
400
800
1200
1600
2000
0 100 200 300 400 500 600 700 800 900 1000

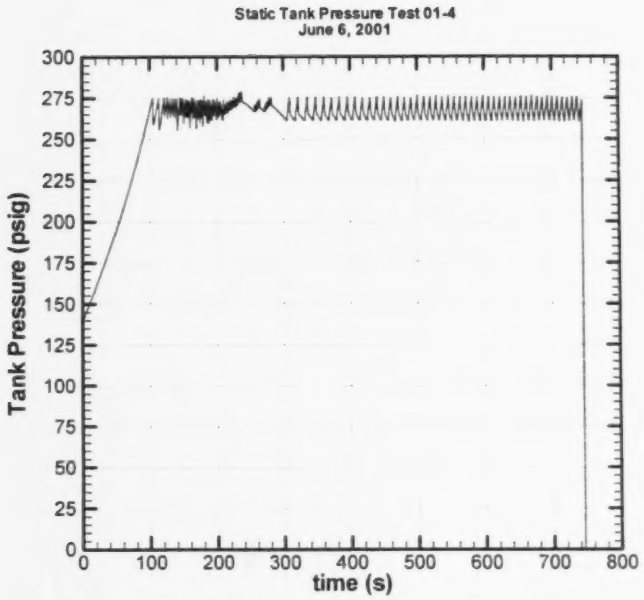

Lading Temperature Bundle 1 Test 01-3
May 31, 2001
Lading Temperature (°C)
time (s)
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280
0 100 200 300 400 500 600 700 800 900 1000

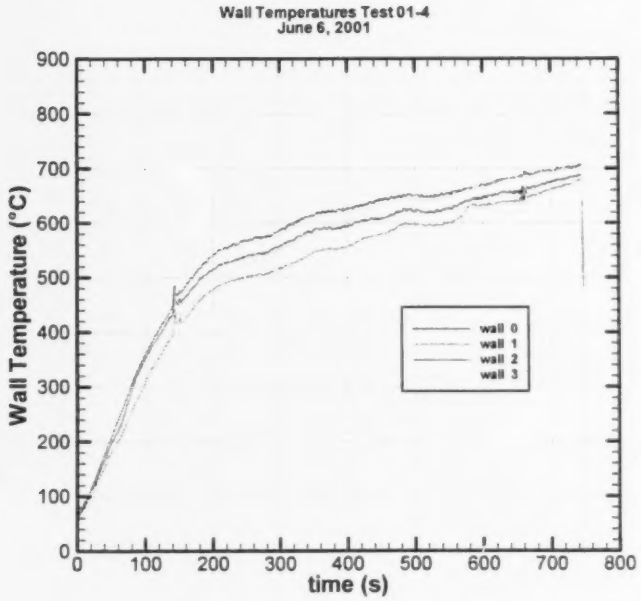

Lading Temperature #2 Test 01-3
May 31, 2001
Lading Temperature (°C)
time (s)
lading 16
lading 18
lading 19
lading 20
lading 21
lading 22
lading 23
lading 24

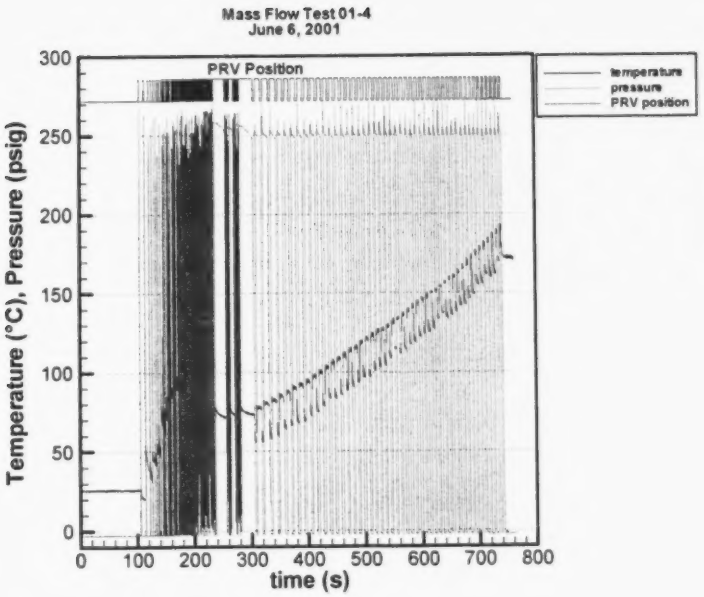

Lading Temperature #4 Test 01-3
May 31, 2001
Lading Temperature (°C)
time (s)
lading 34
lading 35
lading 36
lading 37
lading 38
lading 39
lading 40

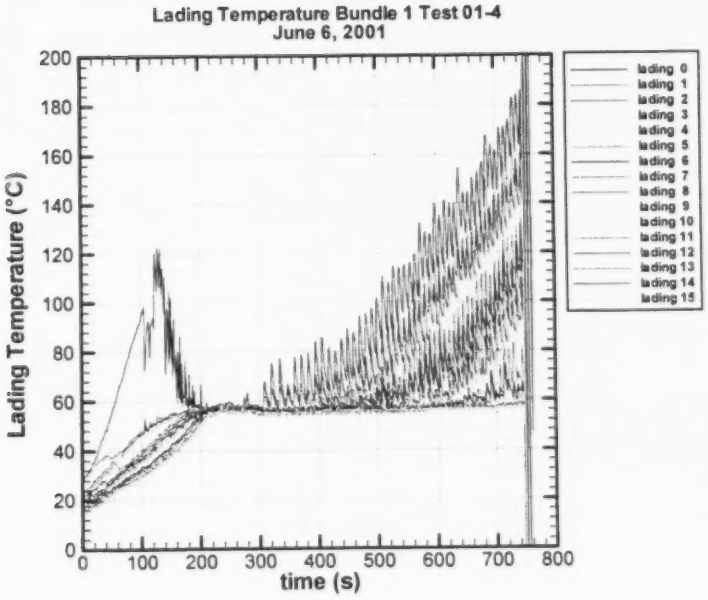

Beta Analysis Test 01-3
May 31, 2001
Temperature (°C)
time (s)
Saturation
Liquid
Vapour
Beta
200
175
150
125
100
75
50
25
0
2
1
0
0
100
200
300
400
500
600
700
800
900
1000

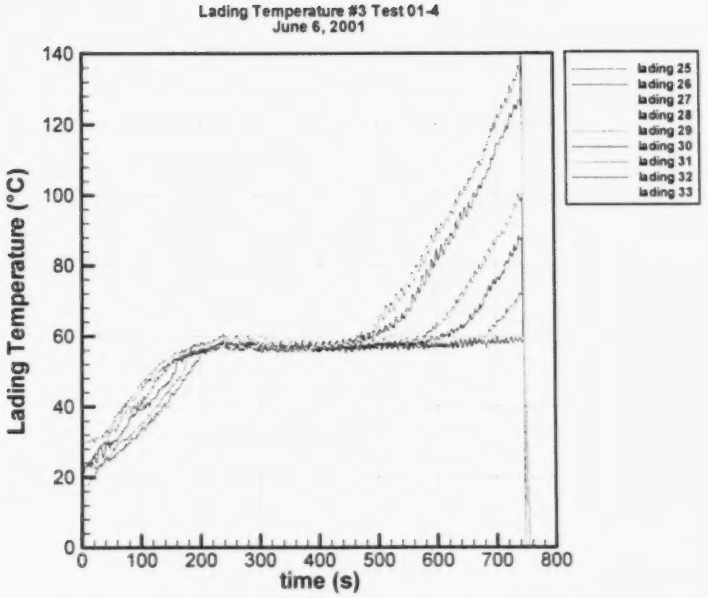

Tank Energy Test 01-3
May 31, 2001
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700
800
900
1000

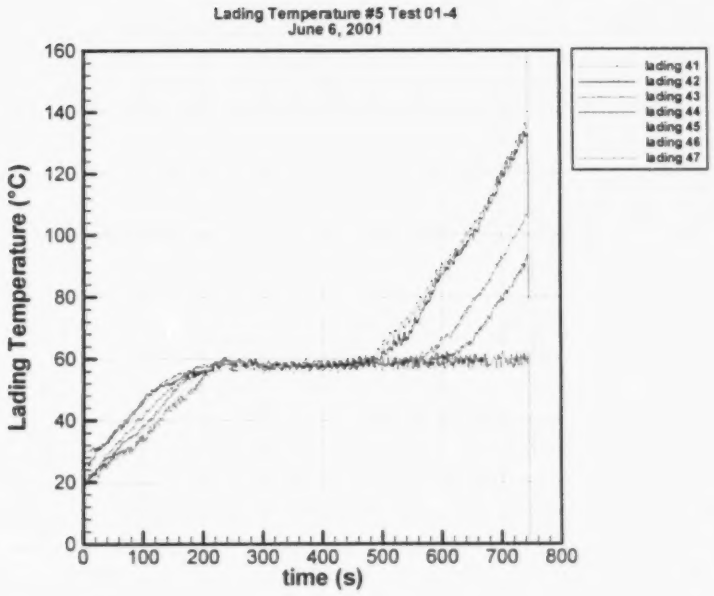

Static Tank Pressure Test 01-4
June 6, 2001
Tank Pressure (psig)
time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
0
100
200
300
400
500
600
700
800

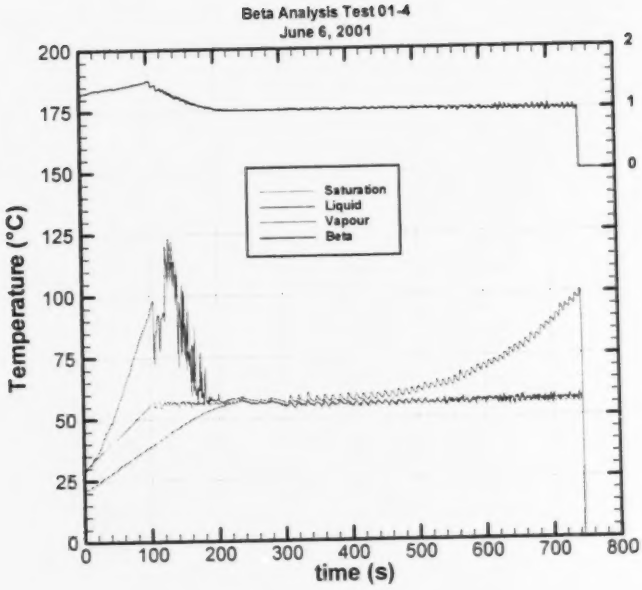

Wall Temperatures Test 01-4
June 6, 2001
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
wall 3
0
100
200
300
400
500
600
700
800
900
0
100
200
300
400
500
600
700
800

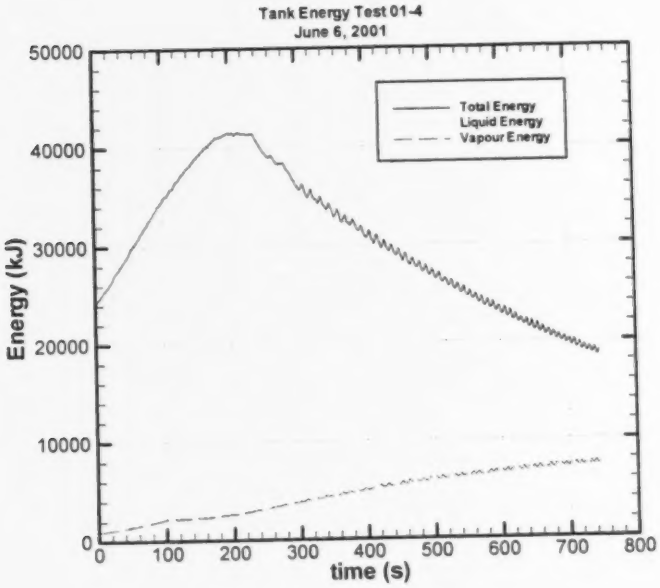

Mass Flow Test 01-4
June 6, 2001
PRV Position
temperature
pressure
PRV position
Temperature (°C), Pressure (psig)
time (s)
0
50
100
150
200
250
300
0
100
200
300
400
500
600
700
800

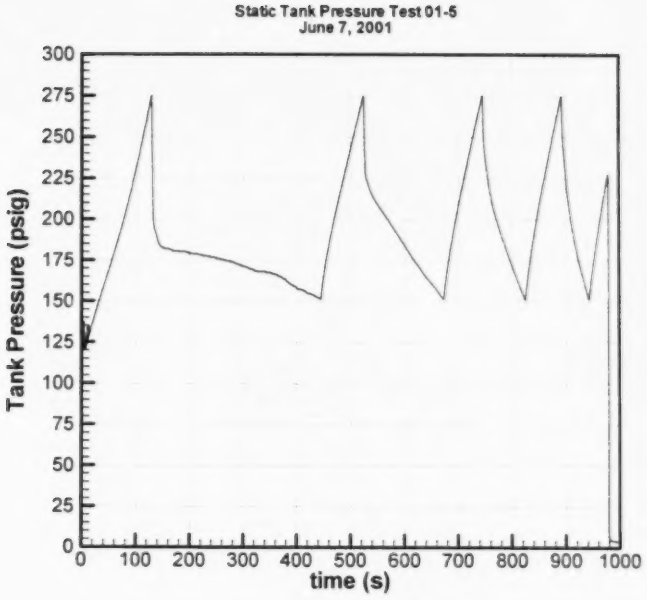

Lading Temperature Bundle 1 Test 01-4
June 6, 2001
Lading Temperature (°C)
time (s)
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800

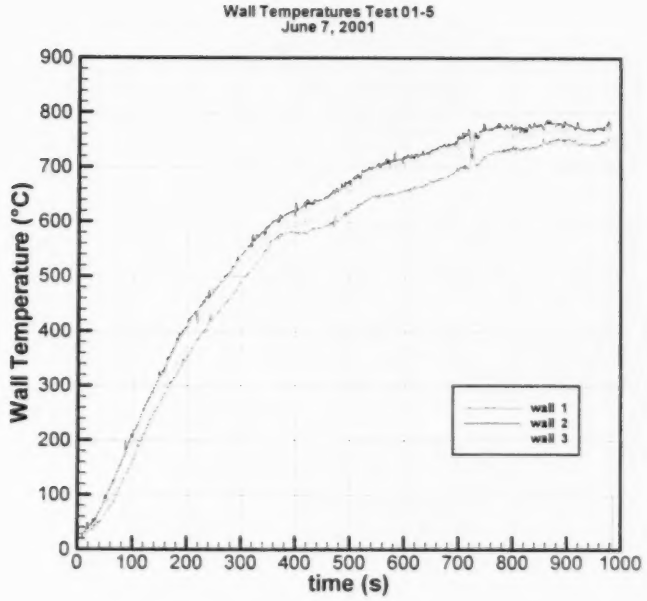

Lading Temperature #3 Test 01-4
June 6, 2001
Lading Temperature (°C)
time (s)
lading 25
lading 26
lading 27
lading 28
lading 29
lading 30
lading 31
lading 32
lading 33

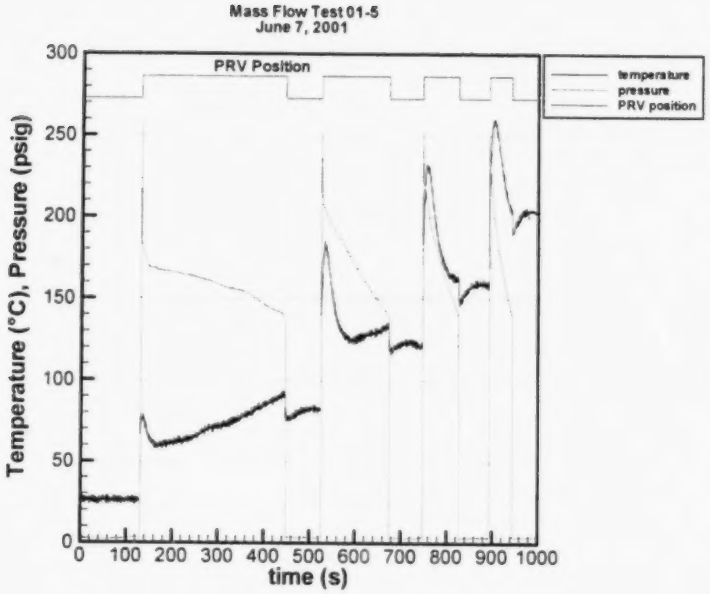

Lading Temperature #5 Test 01-4
June 6, 2001
Lading Temperature (°C)
time (s)
lading 41
lading 42
lading 43
lading 44
lading 45
lading 46
lading 47

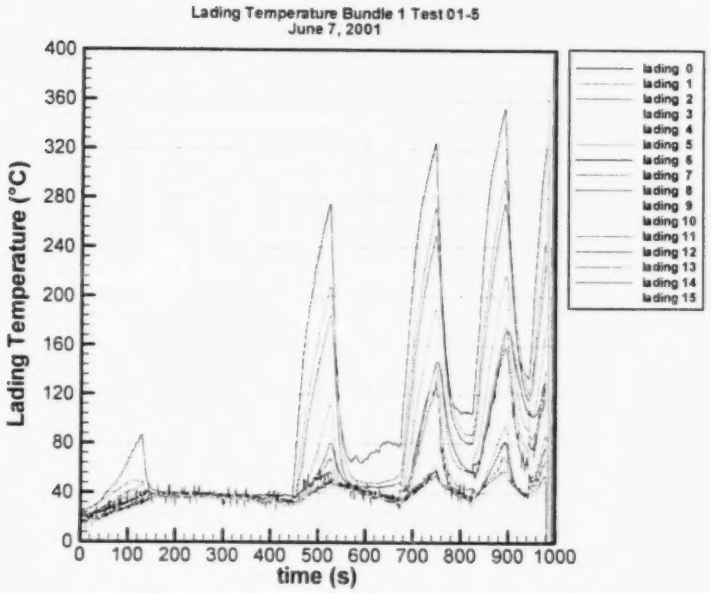

Beta Analysis Test 01-4
June 6, 2001
Temperature (°C)
time (s)
Saturation
Liquid
Vapour
Beta
200
175
150
125
100
75
50
25
0
2
1
0
0
100
200
300
400
500
600
700
800

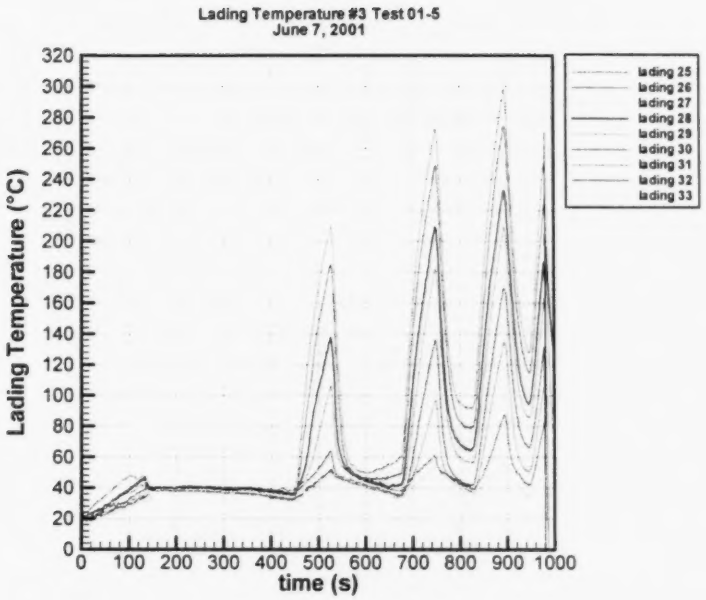

Tank Energy Test 01-4
June 6, 2001
Energy (kJ)
time (s)
Total Energy
Liquid Energy
Vapour Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700
800

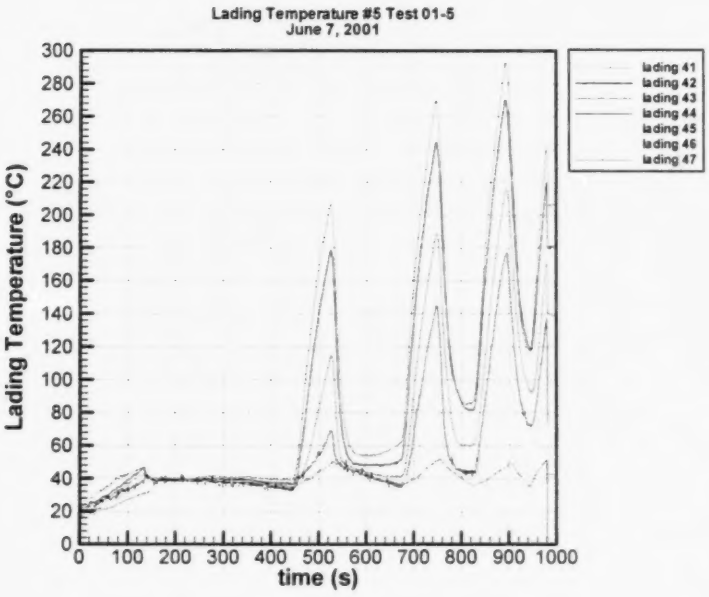

Static Tank Pressure Test 01-5
June 7, 2001
Tank Pressure (psig)
time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
0
100
200
300
400
500
600
700
800
900
1000

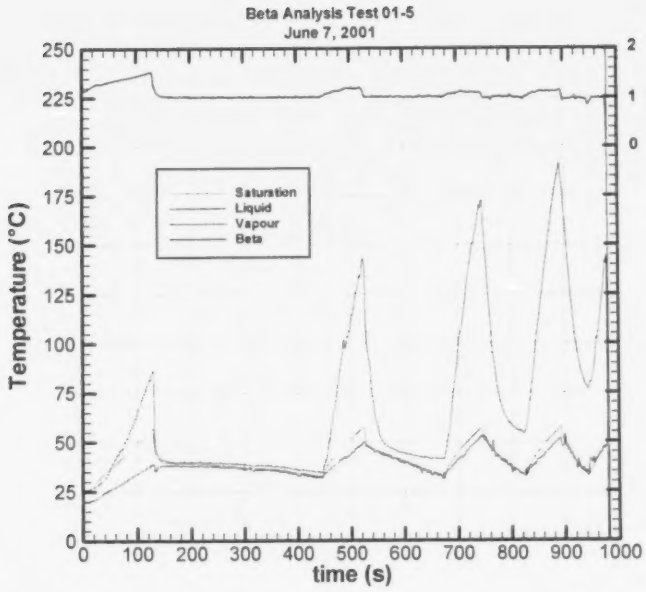

Wall Temperatures Test 01-5
June 7, 2001
Wall Temperature (°C)
time (s)
wall 1
wall 2
wall 3
0
100
200
300
400
500
600
700
800
900
0
100
200
300
400
500
600
700
800
900
1000

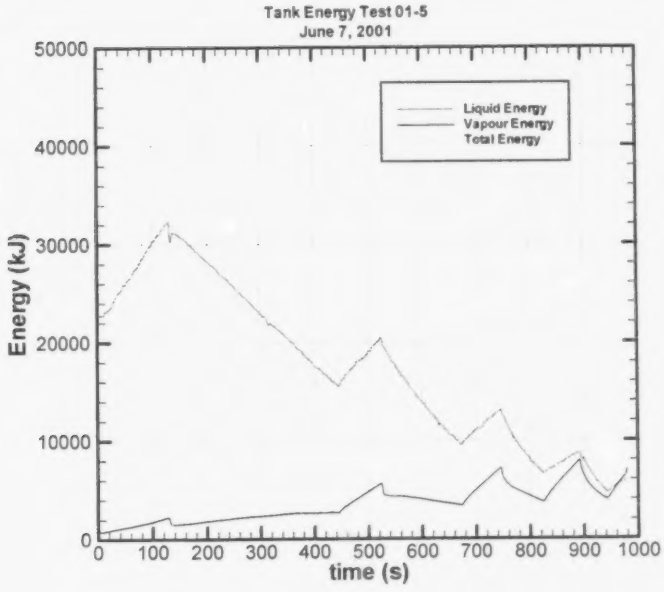

Mass Flow Test 01-5
June 7, 2001
PRV Position
temperature
pressure
PRV position
Temperature (°C), Pressure (psig)
time (s)
0
50
100
150
200
250
300
0 100 200 300 400 500 600 700 800 900 1000

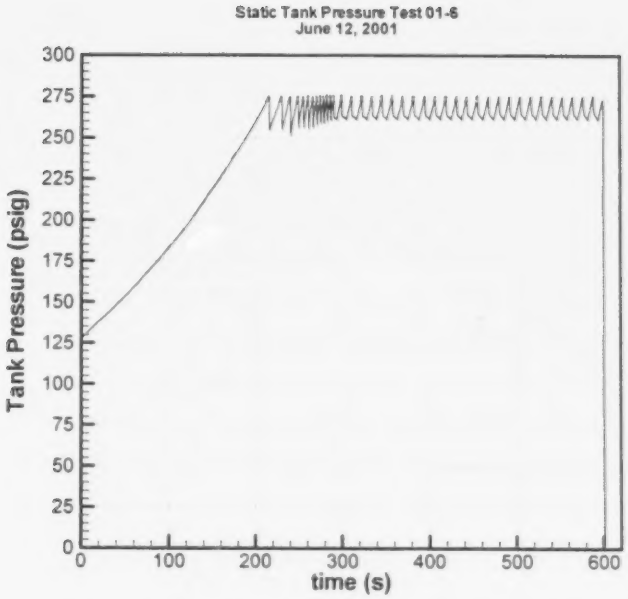

Lading Temperature Bundle 1 Test 01-5
June 7, 2001
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
Lading Temperature (°C)
time (s)
0
40
80
120
160
200
240
280
320
360
400
0 100 200 300 400 500 600 700 800 900 1000

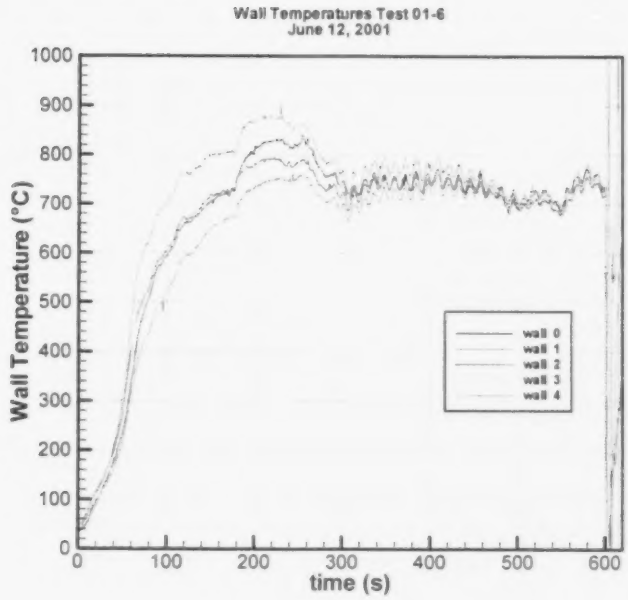

Lading Temperature #3 Test 01-5
June 7, 2001
Lading Temperature (°C)
time (s)
lading 25
lading 26
lading 27
lading 28
lading 29
lading 30
lading 31
lading 32
lading 33

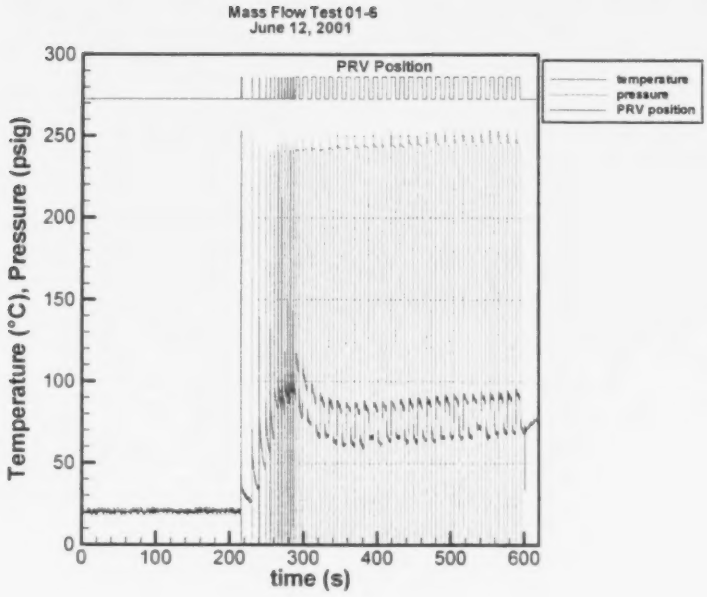

Lading Temperature #5 Test 01-5
June 7, 2001
Lading Temperature (°C)
time (s)
lading 41
lading 42
lading 43
lading 44
lading 45
lading 46
lading 47

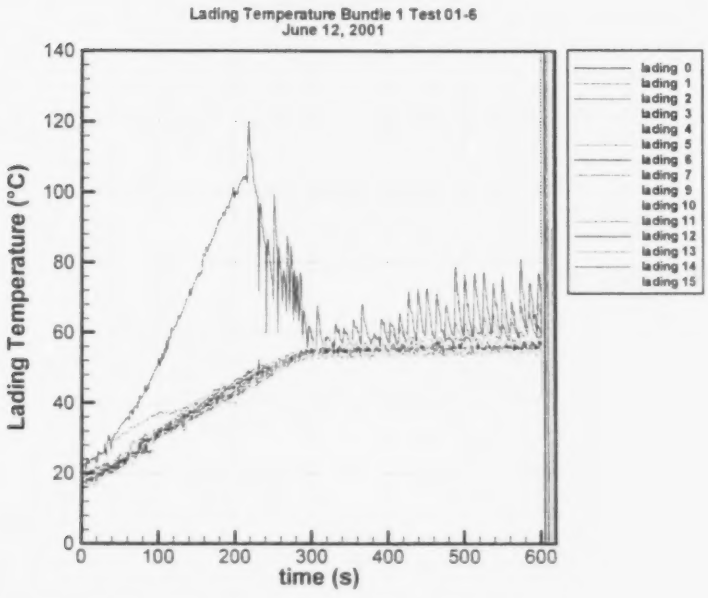

Beta Analysis Test 01-5
June 7, 2001
Temperature (°C)
time (s)
Saturation
Liquid
Vapour
Beta
250
225
200
175
150
125
100
75
50
25
0
2
1
0
0
100
200
300
400
500
600
700
800
900
1000

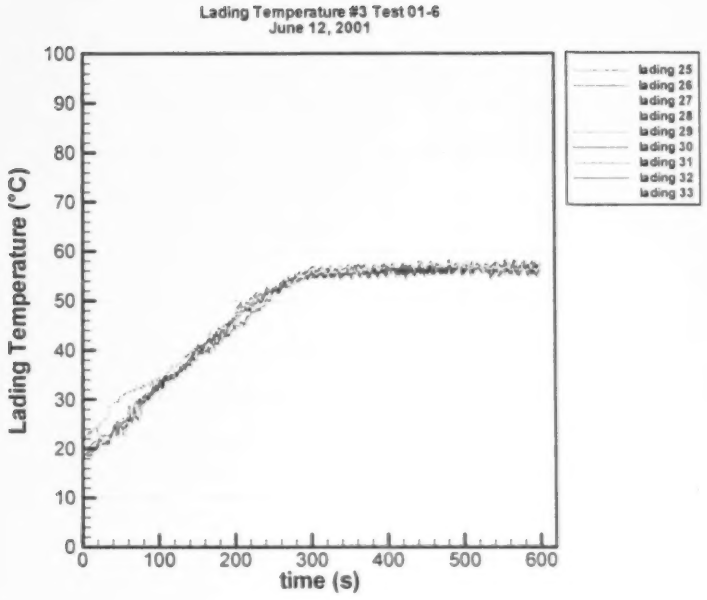

Tank Energy Test 01-5
June 7, 2001
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700
800
900
1000

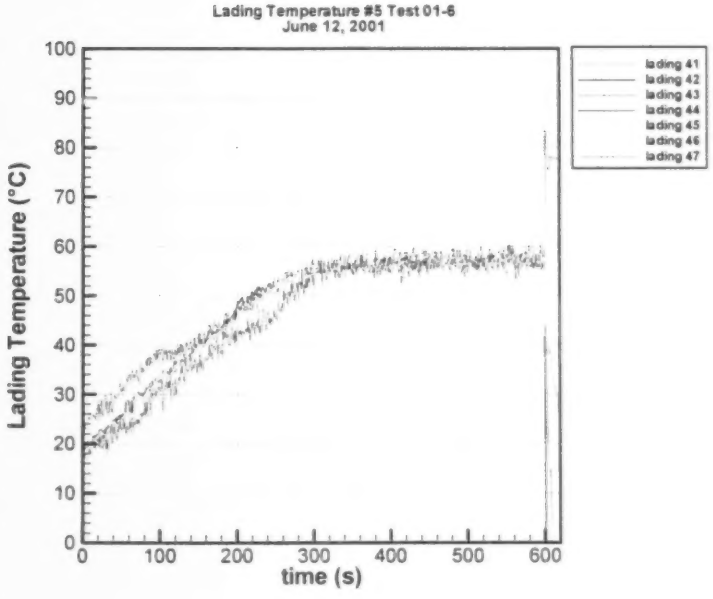

Static Tank Pressure Test 01-6
June 12, 2001
Tank Pressure (psig)
time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
0
100
200
300
400
500
600

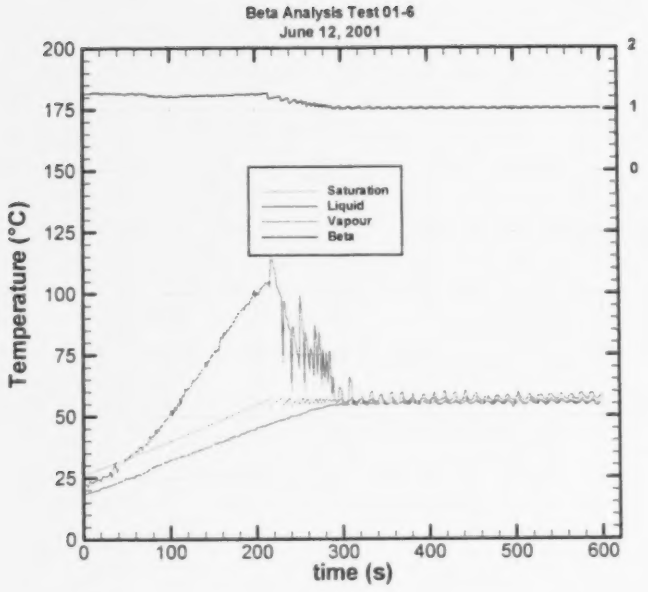

Wall Temperatures Test 01-6
June 12, 2001
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
wall 3
wall 4
0
100
200
300
400
500
600
700
800
900
1000
0
100
200
300
400
500
600

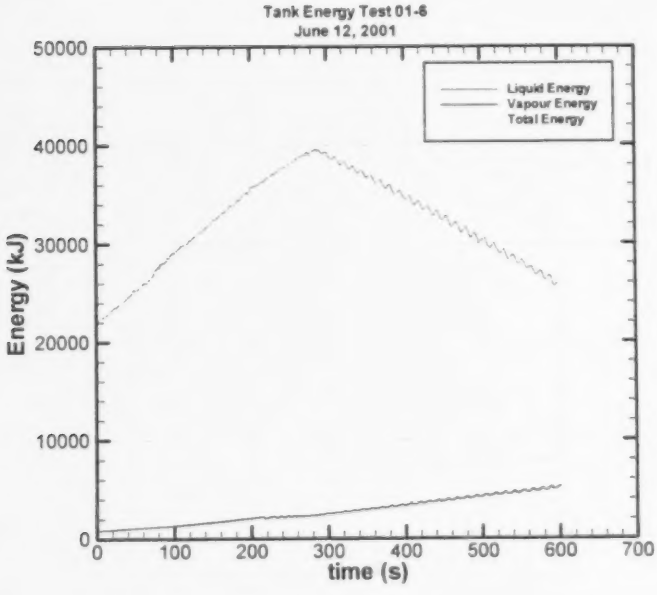

Mass Flow Test 01-6
June 12, 2001
PRV Position
temperature
pressure
PRV position
Temperature (°C), Pressure (psig)
time (s)
0
50
100
150
200
250
300
0
100
200
300
400
500
600

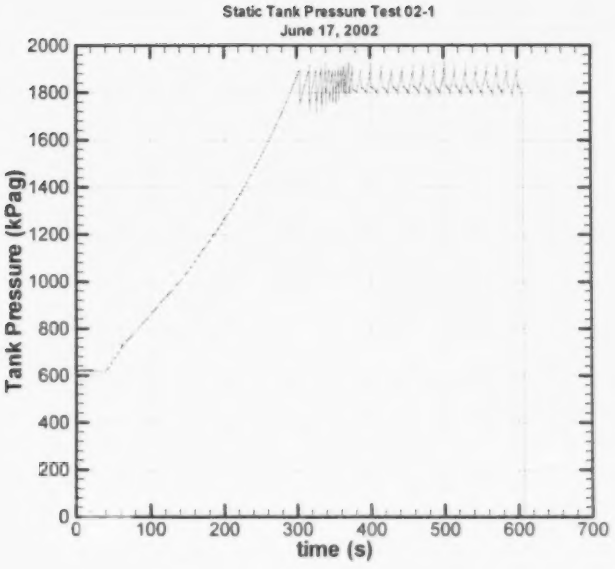

Lading Temperature Bundle 1 Test 01-6
June 12, 2001
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
Lading Temperature (°C)
time (s)
0
20
40
60
80
100
120
140
0
100
200
300
400
500
600

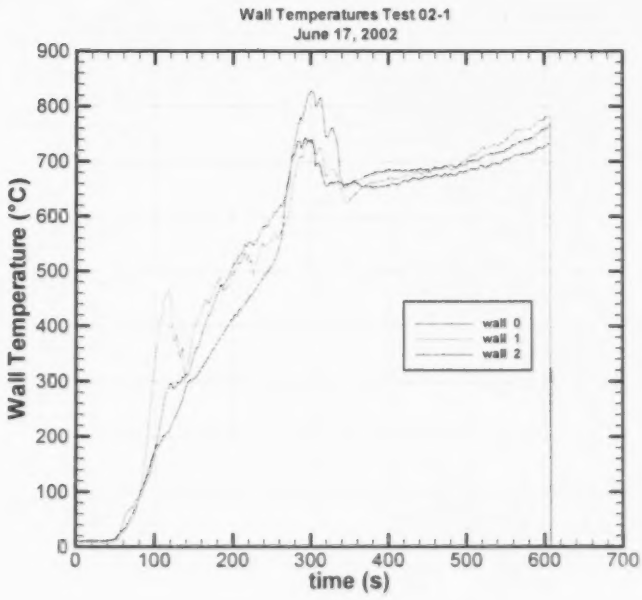

Lading Temperature #3 Test 01-6
June 12, 2001
Lading Temperature (°C)
time (s)
lading 25
lading 26
lading 27
lading 28
lading 29
lading 30
lading 31
lading 32
lading 33

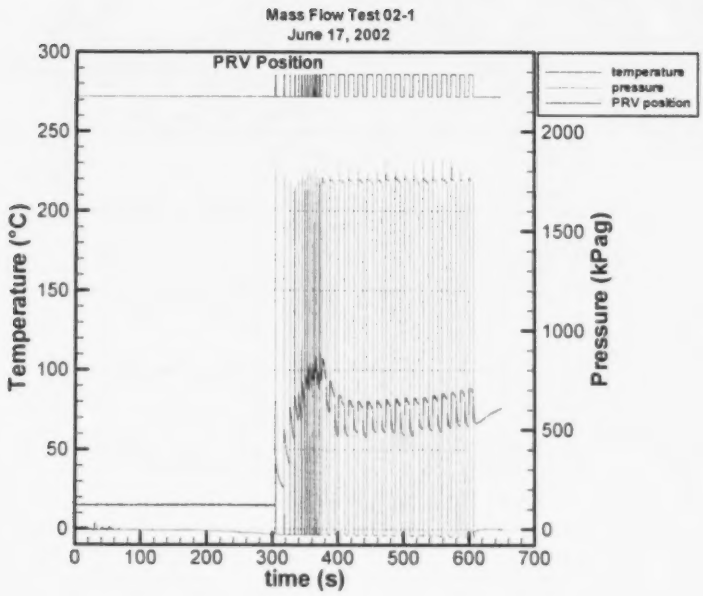

Lading Temperature #5 Test 01-6
June 12, 2001
Lading Temperature (°C)
time (s)
lading 41
lading 42
lading 43
lading 44
lading 45
lading 46
lading 47

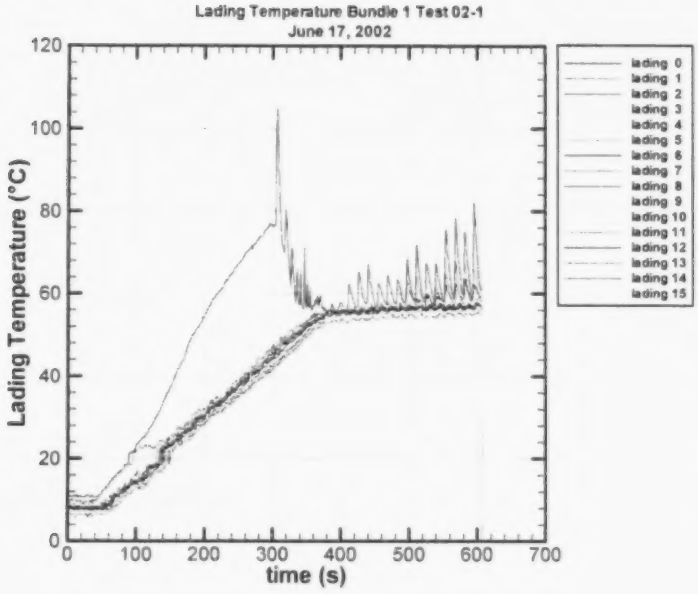

Beta Analysis Test 01-6
June 12, 2001
Temperature (°C)
time (s)
Saturation
Liquid
Vapour
Beta
200
175
150
125
100
75
50
25
0
2
1
0
0
100
200
300
400
500
600

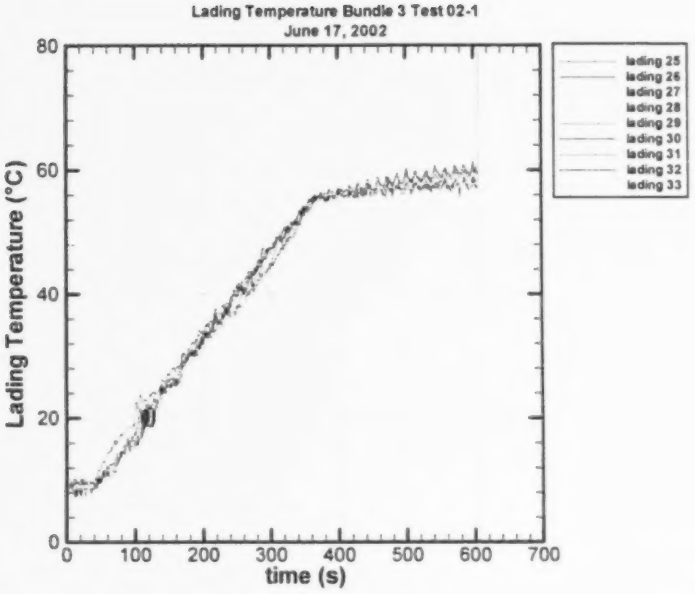

Tank Energy Test 01-6
June 12, 2001
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700

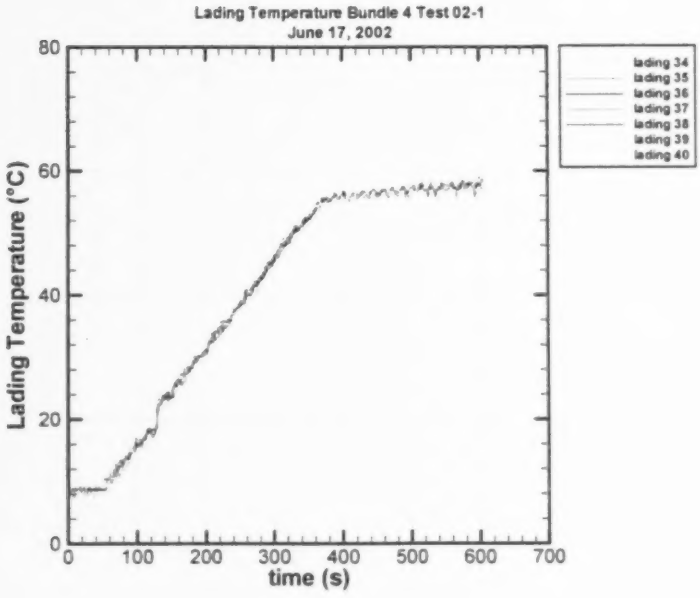

Static Tank Pressure Test 02-1
June 17, 2002
Tank Pressure (kPag)
time (s)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
100
200
300
400
500
600
700

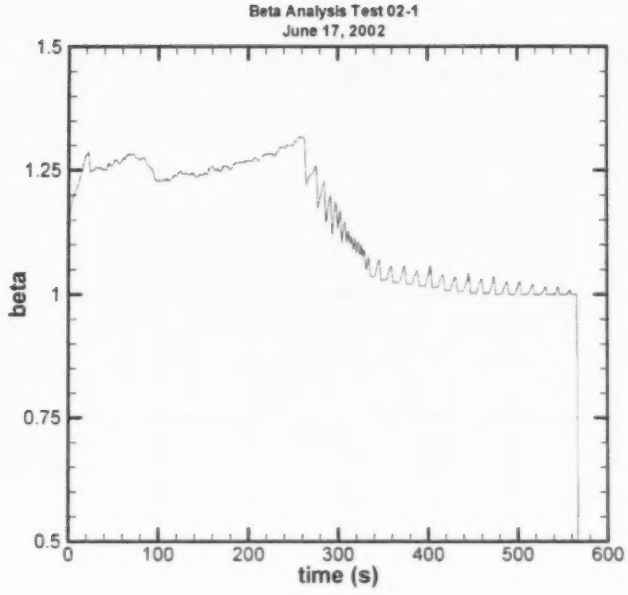

Wall Temperatures Test 02-1
June 17, 2002
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
0
100
200
300
400
500
600
700
800
900
0
100
200
300
400
500
600
700

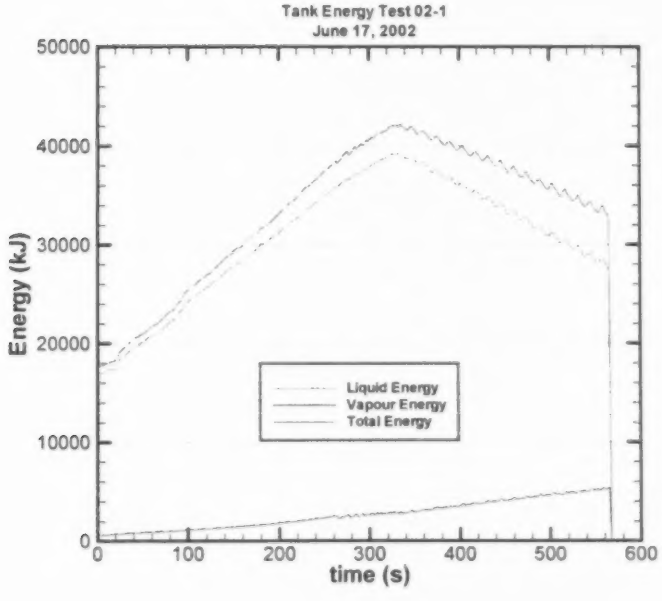

Mass Flow Test 02-1
June 17, 2002
PRV Position
temperature
pressure
PRV position
Temperature (°C)
Pressure (kPag)
time (s)
0
50
100
150
200
250
300
500
1000
1500
2000
0
100
200
300
400
500
600
700

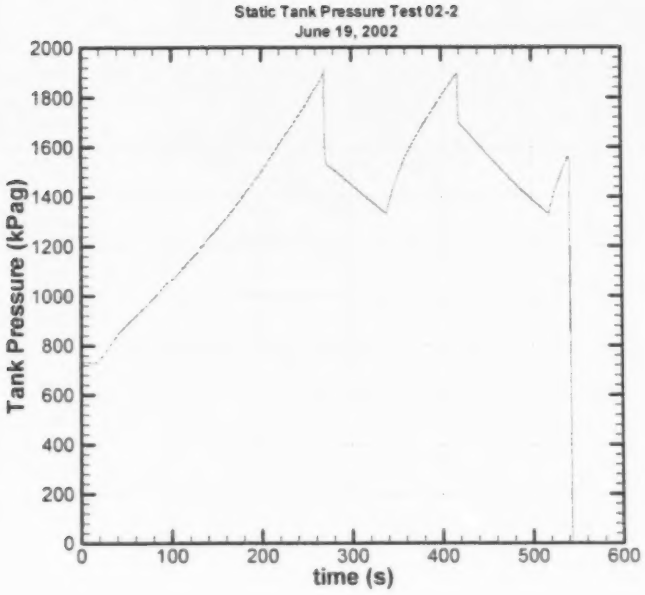

Lading Temperature Bundle 1 Test 02-1
June 17, 2002
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
Lading Temperature (°C)
time (s)
0
20
40
60
80
100
120
0
100
200
300
400
500
600
700

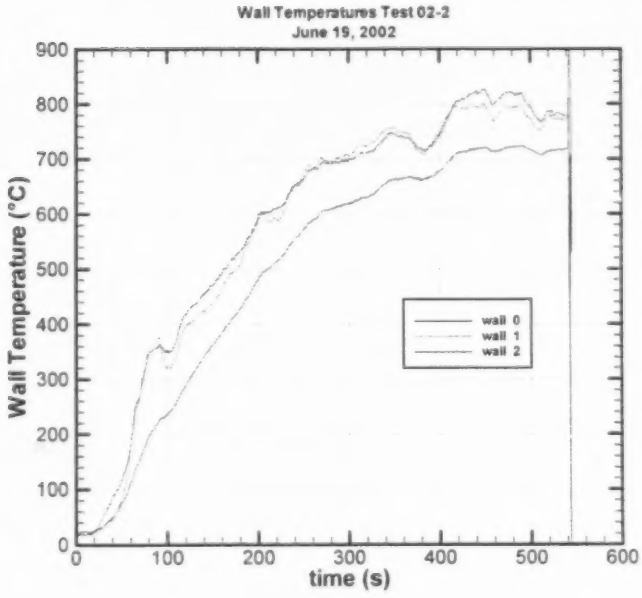

Lading Temperature Bundle 3 Test 02-1
June 17, 2002
Lading Temperature (°C)
time (s)
0
20
40
60
80
0
100
200
300
400
500
600
700
lading 25
lading 26
lading 27
lading 28
lading 29
lading 30
lading 31
lading 32
lading 33

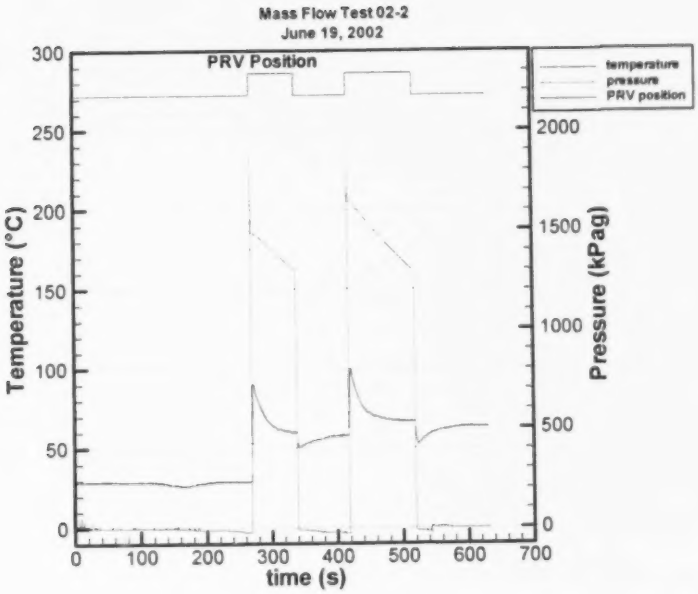

Lading Temperature Bundle 4 Test 02-1
June 17, 2002
Lading Temperature (°C)
time (s)
0
20
40
60
80
0
100
200
300
400
500
600
700
lading 34
lading 35
lading 36
lading 37
lading 38
lading 39
lading 40

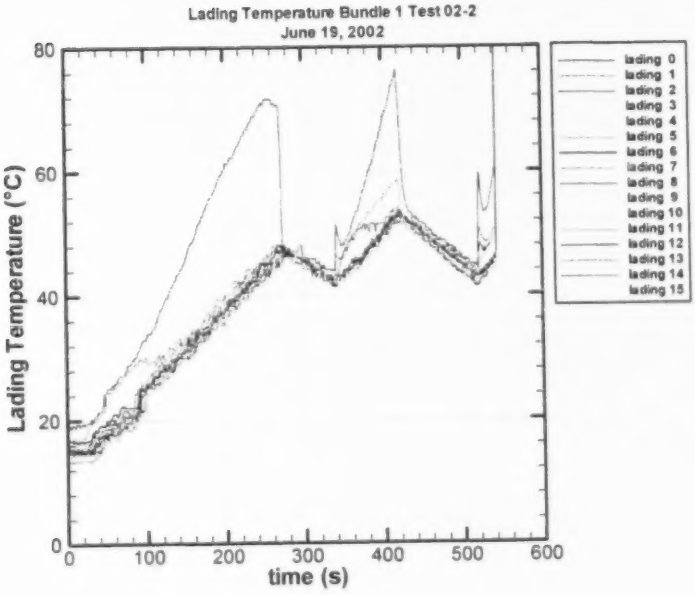

Beta Analysis Test 02-1
June 17, 2002
beta
time (s)
1.5
1.25
1
0.75
0.5
0
100
200
300
400
500
600

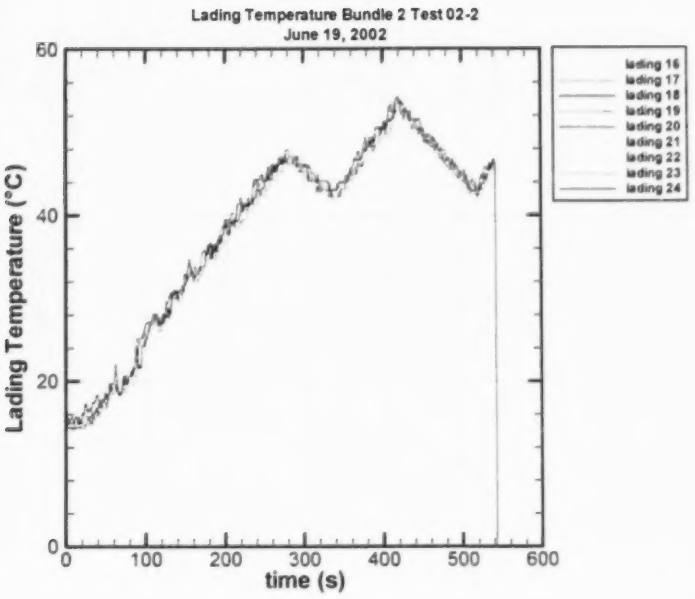

Tank Energy Test 02-1
June 17, 2002
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600

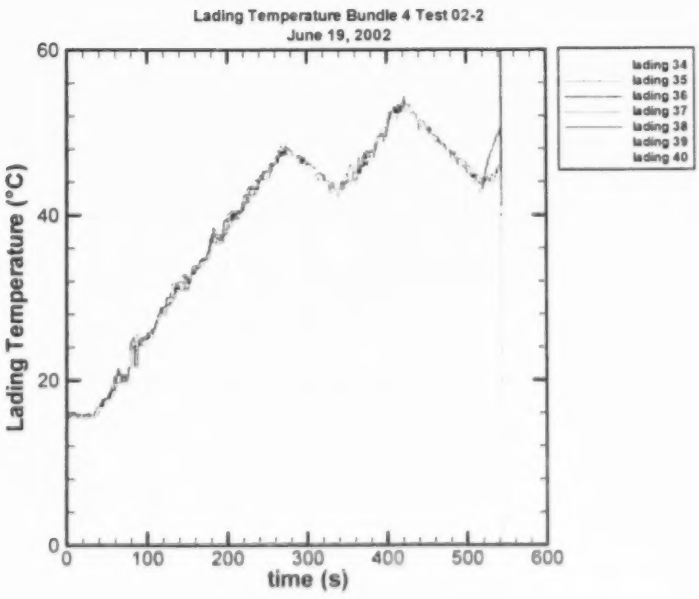

Static Tank Pressure Test 02-2
June 19, 2002
Tank Pressure (kPag)
time (s)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
100
200
300
400
500
600

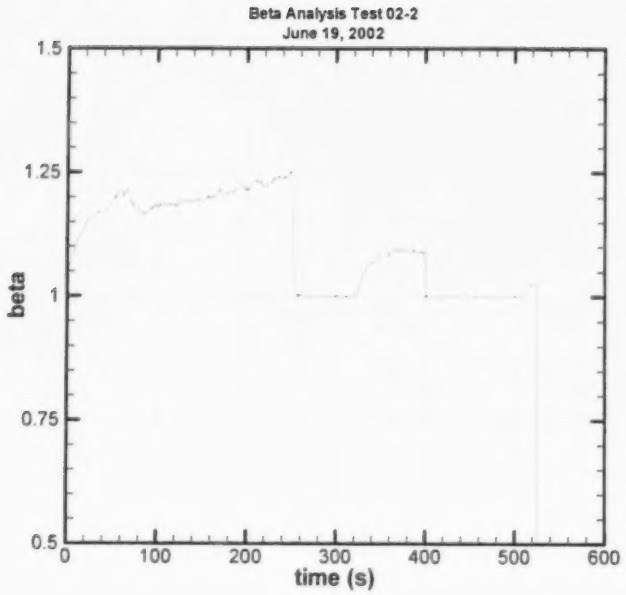

Wall Temperatures Test 02-2
June 19, 2002
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
0
100
200
300
400
500
600
700
800
900
0
100
200
300
400
500
600

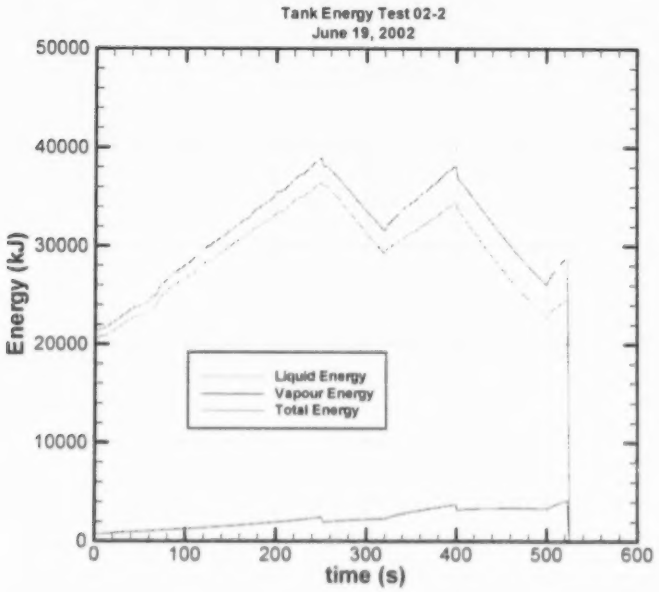

Mass Flow Test 02-2
June 19, 2002
PRV Position
temperature
pressure
PRV position
Temperature (°C)
Pressure (kPag)
time (s)
0
50
100
150
200
250
300
500
1000
1500
2000
0
100
200
300
400
500
600
700

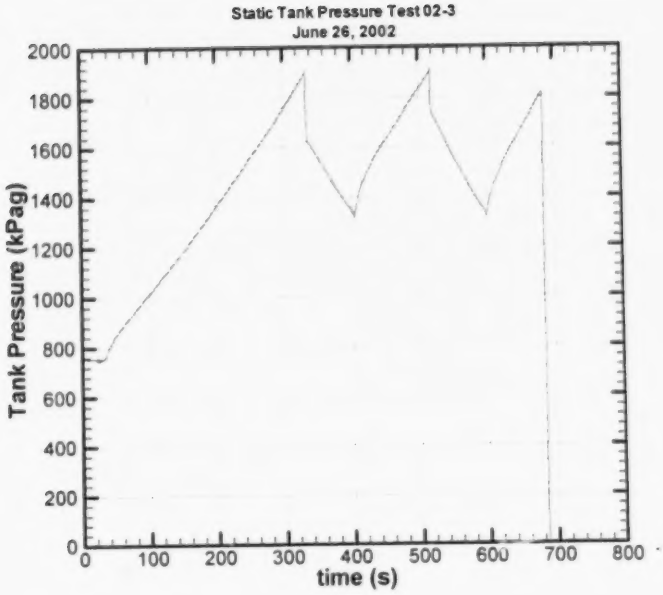

Lading Temperature Bundle 1 Test 02-2
June 19, 2002
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
Lading Temperature (°C)
time (s)
0
20
40
60
80
0
100
200
300
400
500
600

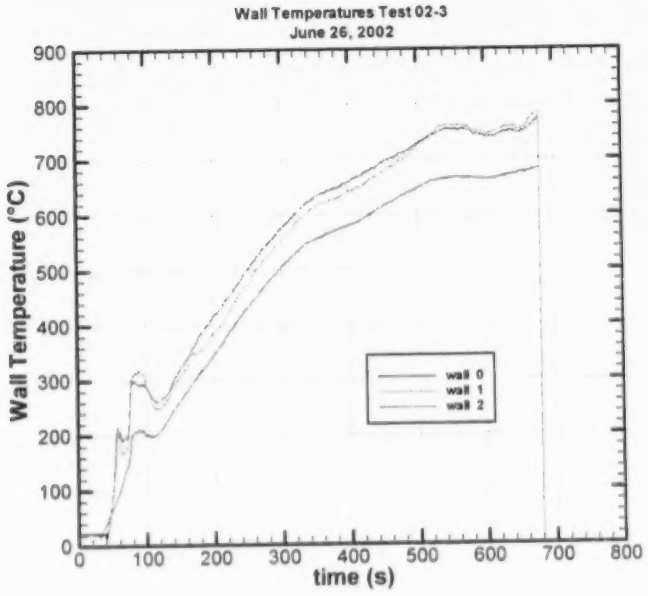

Lading Temperature Bundle 2 Test 02-2
June 19, 2002
Lading Temperature (°C)
time (s)
0
20
40
60
0
100
200
300
400
500
600
lading 16
lading 17
lading 18
lading 19
lading 20
lading 21
lading 22
lading 23
lading 24

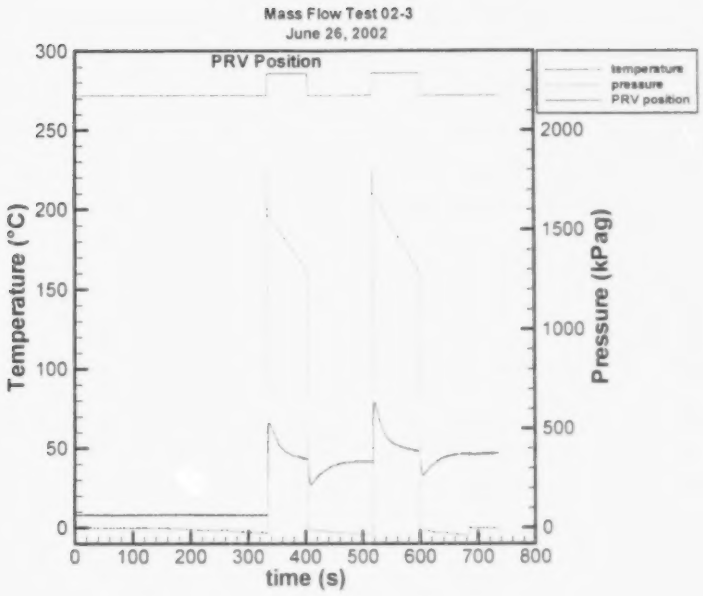

Lading Temperature Bundle 4 Test 02-2
June 19, 2002
Lading Temperature (°C)
time (s)
0
20
40
60
0
100
200
300
400
500
600
lading 34
lading 35
lading 36
lading 37
lading 38
lading 39
lading 40

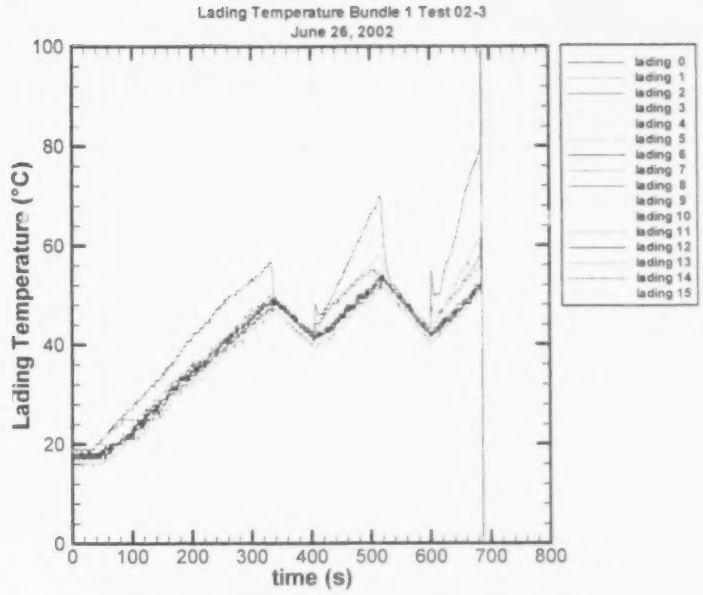

Beta Analysis Test 02-2
June 19, 2002
beta
time (s)
1.5
1.25
1
0.75
0.5
0
100
200
300
400
500
600

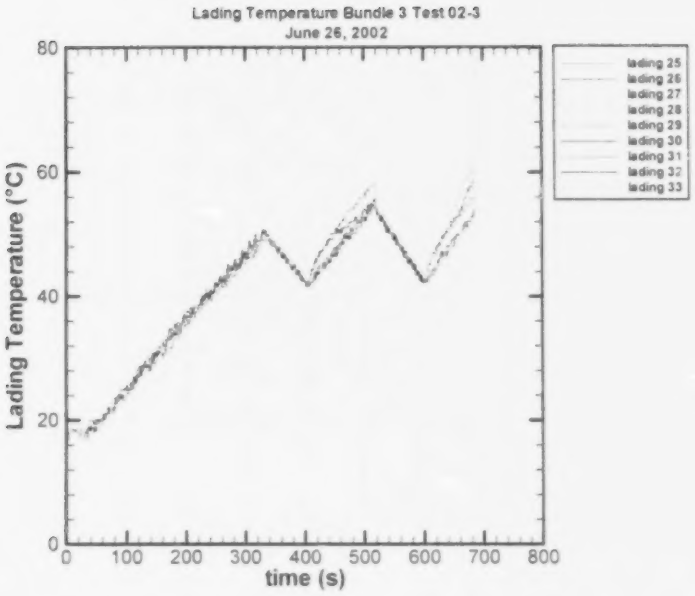

Tank Energy Test 02-2
June 19, 2002
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600

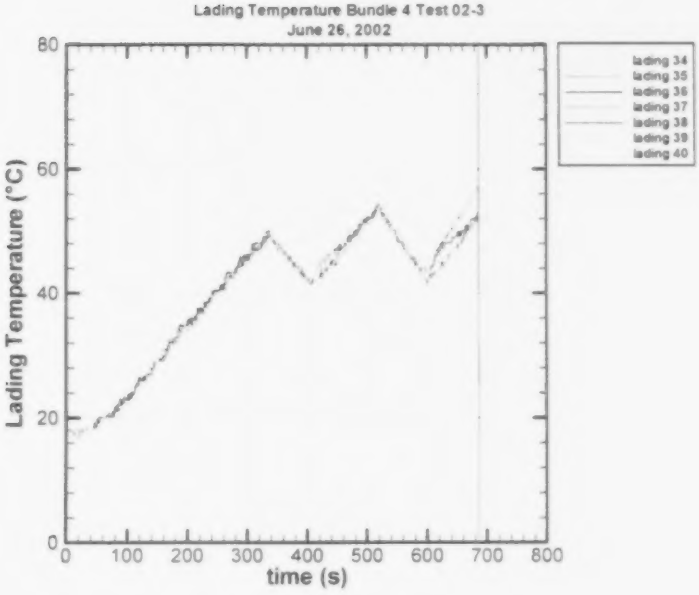

Static Tank Pressure Test 02-3
June 26, 2002
Tank Pressure (kPag)
time (s)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
100
200
300
400
500
600
700
800

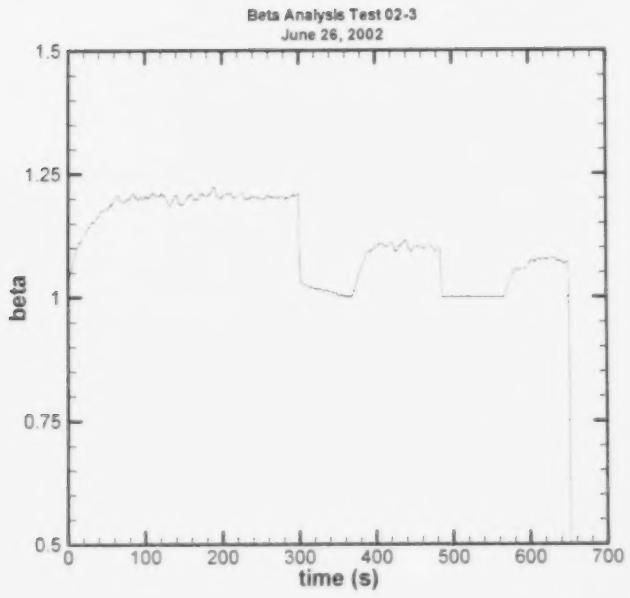

Wall Temperatures Test 02-3
June 26, 2002
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
0
100
200
300
400
500
600
700
800
900
0
100
200
300
400
500
600
700
800

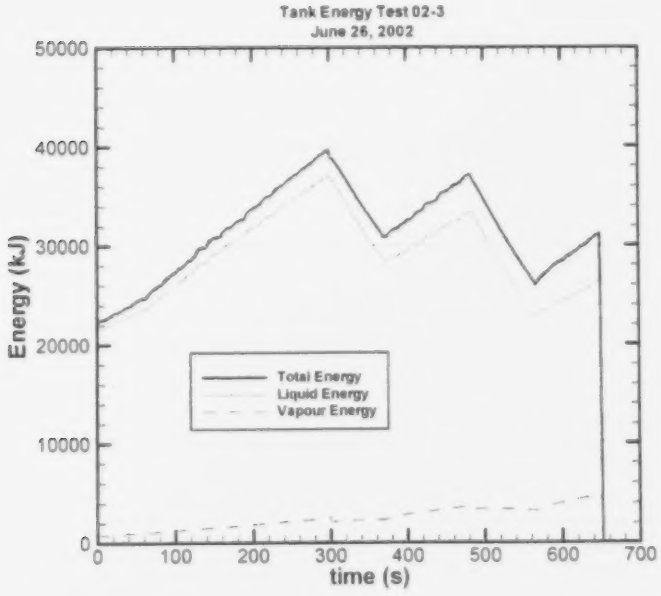

Mass Flow Test 02-3
June 26, 2002
PRV Position
temperature
pressure
PRV position
Temperature (°C)
Pressure (kPag)
time (s)
0
50
100
150
200
250
300
500
1000
1500
2000
0
100
200
300
400
500
600
700
800

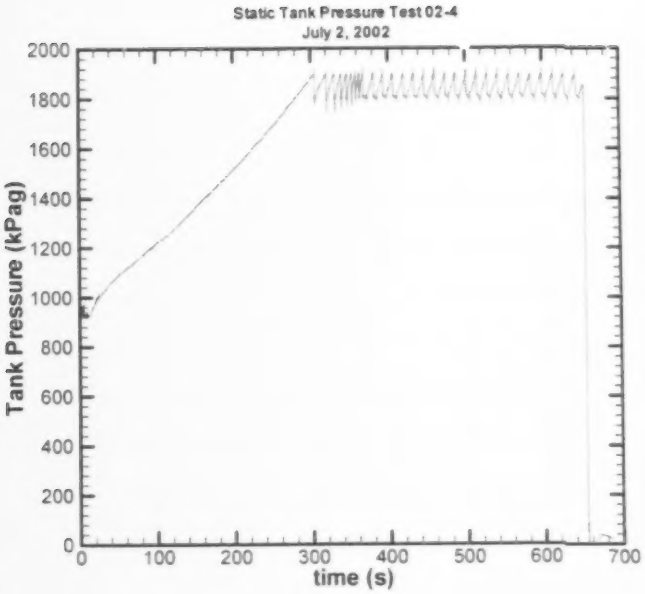

Lading Temperature Bundle 1 Test 02-3
June 26, 2002
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
Lading Temperature (°C)
time (s)
0
20
40
60
80
100
0
100
200
300
400
500
600
700
800

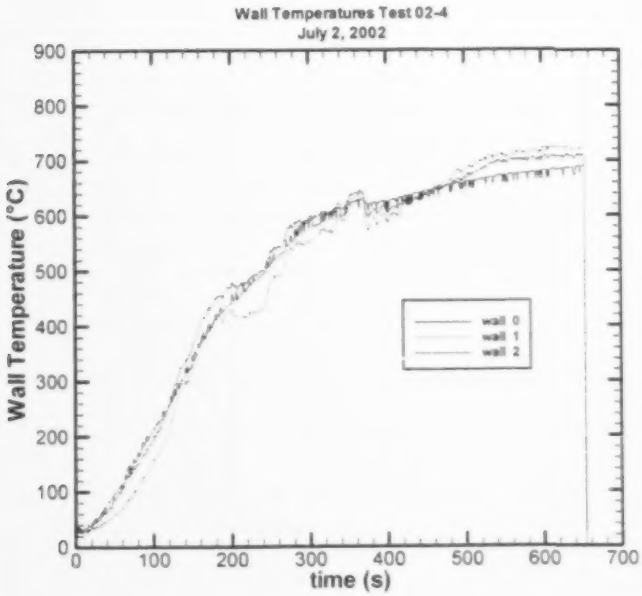

Lading Temperature Bundle 3 Test 02-3
June 26, 2002
Lading Temperature (°C)
time (s)
0
20
40
60
80
0
100
200
300
400
500
600
700
800
lading 25
lading 26
lading 27
lading 28
lading 29
lading 30
lading 31
lading 32
lading 33

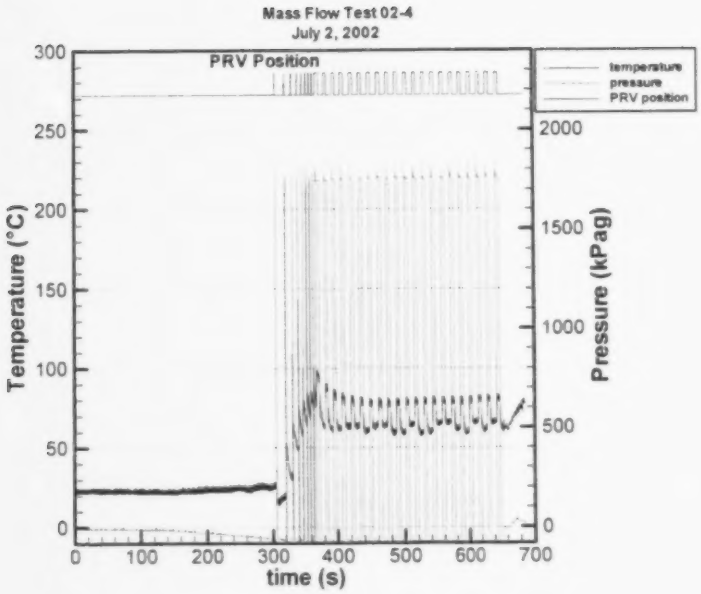

Lading Temperature Bundle 4 Test 02-3
June 26, 2002
Lading Temperature (°C)
time (s)
0
20
40
60
80
0
100
200
300
400
500
600
700
800
lading 34
lading 35
lading 36
lading 37
lading 38
lading 39
lading 40

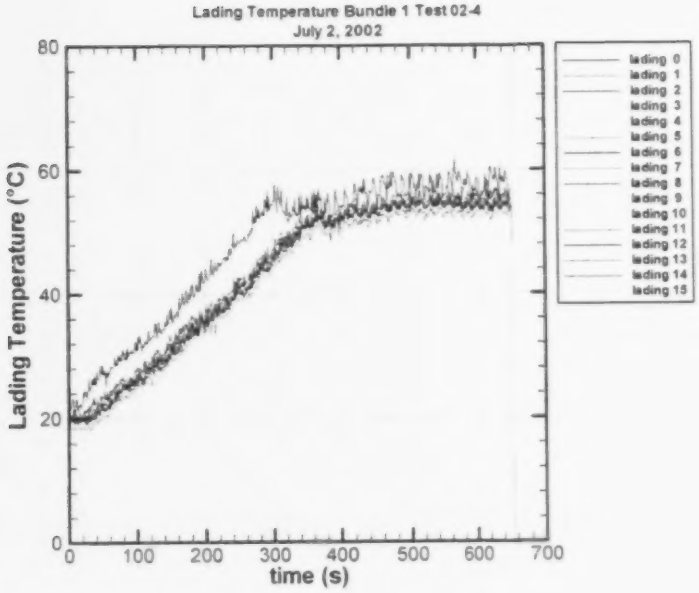

Beta Analysis Test 02-3
June 26, 2002
beta
time (s)
1.5
1.25
1
0.75
0.5
0
100
200
300
400
500
600
700

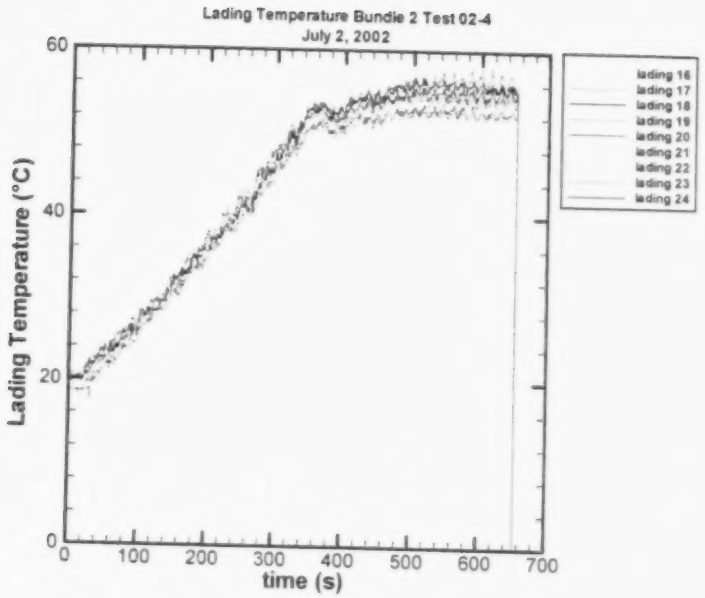

Tank Energy Test 02-3
June 26, 2002
Energy (kJ)
time (s)
Total Energy
Liquid Energy
Vapour Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700

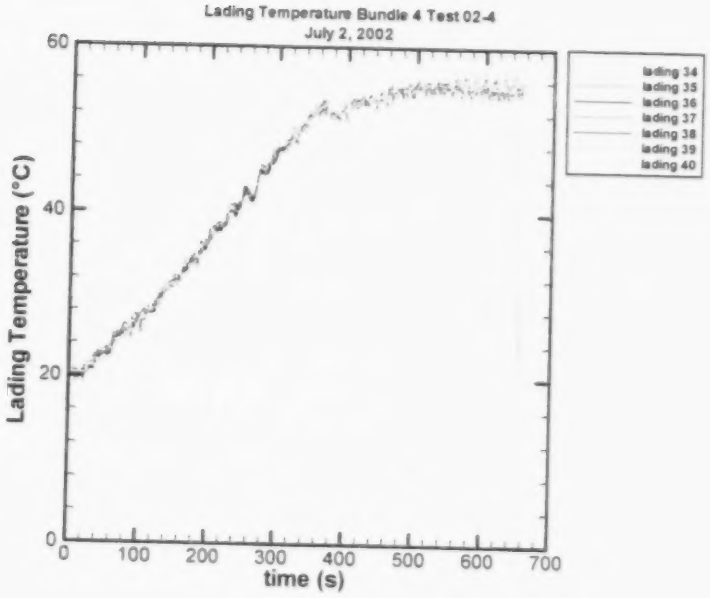

Static Tank Pressure Test 02-4
July 2, 2002
Tank Pressure (kPag)
time (s)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
100
200
300
400
500
600
700

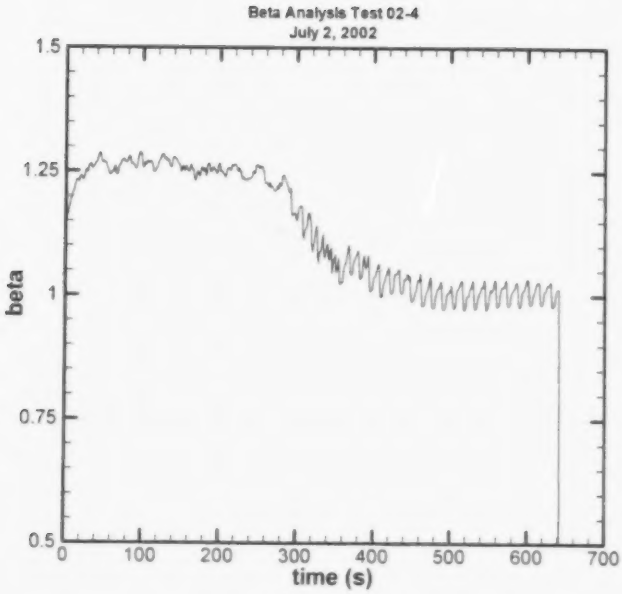

Wall Temperatures Test 02-4
July 2, 2002
Wall Temperature (°C)
time (s)
wall 0
wall 1
wall 2
0
100
200
300
400
500
600
700
800
900
0
100
200
300
400
500
600
700

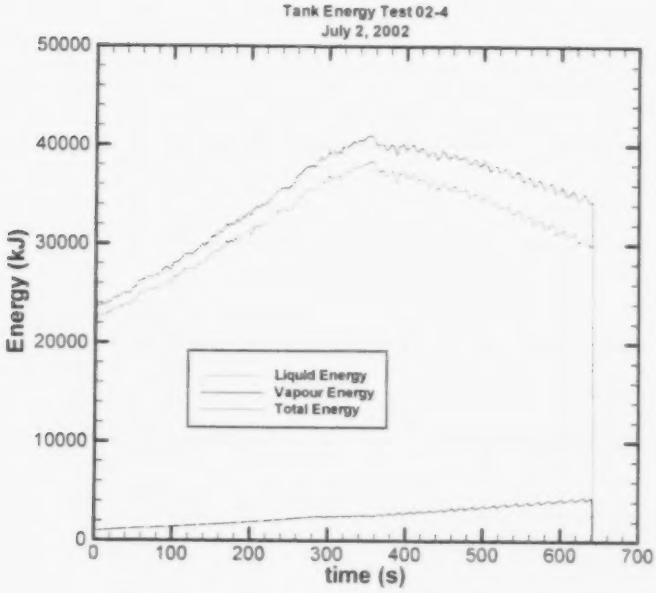

Mass Flow Test 02-4
July 2, 2002
PRV Position
temperature
pressure
PRV position
Temperature (°C)
Pressure (kPag)
time (s)
0
50
100
150
200
250
300
500
1000
1500
2000
0
100
200
300
400
500
600
700


Lading Temperature Bundle 1 Test 02-4
July 2, 2002
Lading Temperature (°C)
time (s)
lading 0
lading 1
lading 2
lading 3
lading 4
lading 5
lading 6
lading 7
lading 8
lading 9
lading 10
lading 11
lading 12
lading 13
lading 14
lading 15
0
20
40
60
80
0
100
200
300
400
500
600
700


Lading Temperature Bundle 2 Test 02-4
July 2, 2002
Lading Temperature (°C)
time (s)
0
20
40
60
0
100
200
300
400
500
600
700
lading 16
lading 17
lading 18
lading 19
lading 20
lading 21
lading 22
lading 23
lading 24

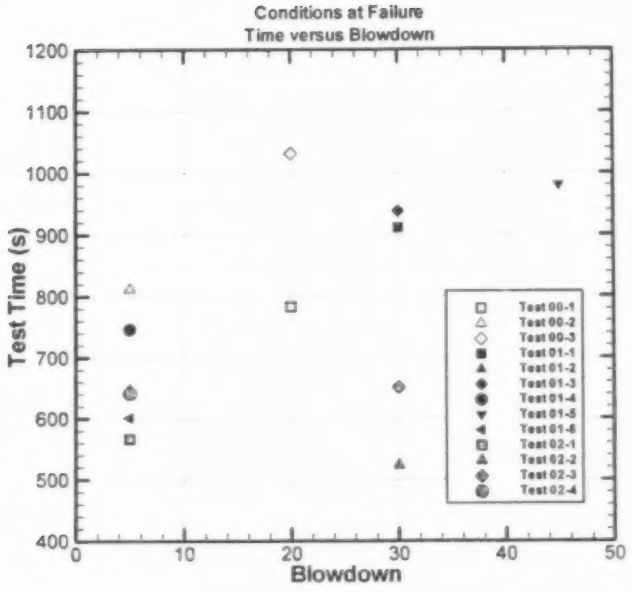

Lading Temperature Bundle 4 Test 02-4
July 2, 2002
Lading Temperature (°C)
time (s)
0
20
40
60
0
100
200
300
400
500
600
700
lading 34
lading 35
lading 36
lading 37
lading 38
lading 39
lading 40

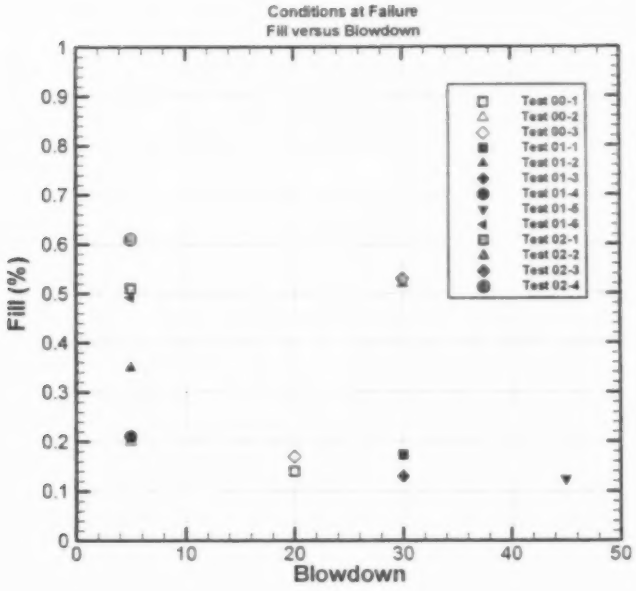

Beta Analysis Test 02-4
July 2, 2002
beta
time (s)
1.5
1.25
1
0.75
0.5
0
100
200
300
400
500
600
700

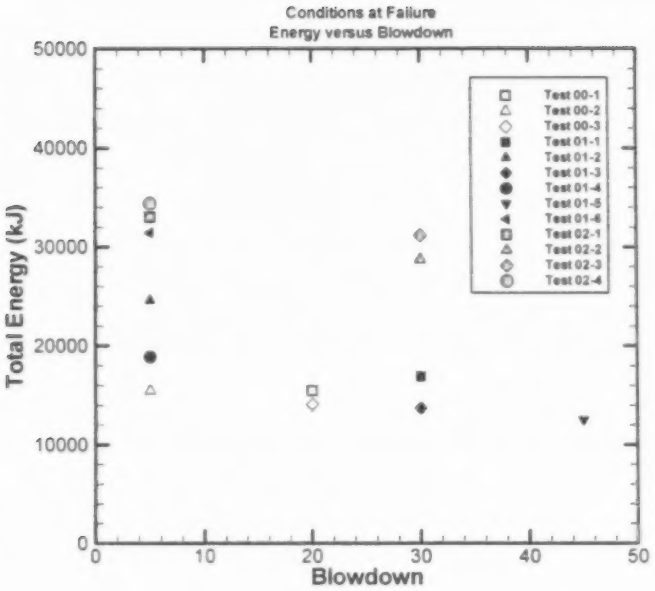

Tank Energy Test 02-4
July 2, 2002
Energy (kJ)
time (s)
Liquid Energy
Vapour Energy
Total Energy
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700

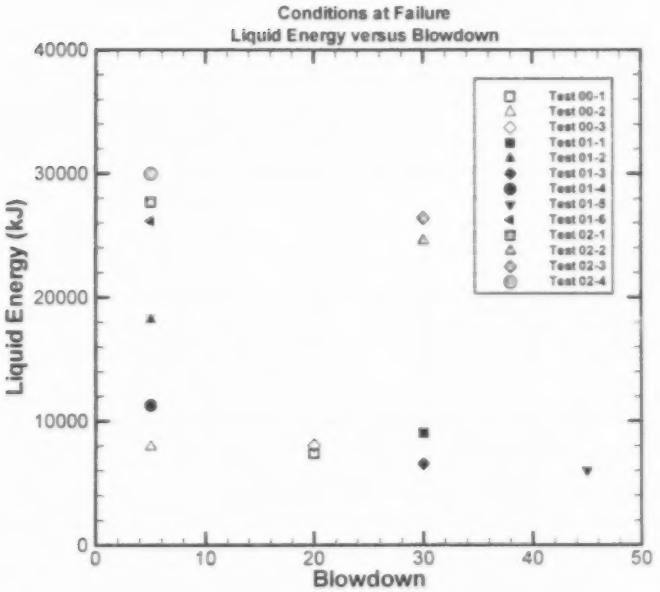
Appendix F: Additional Analysis Plots

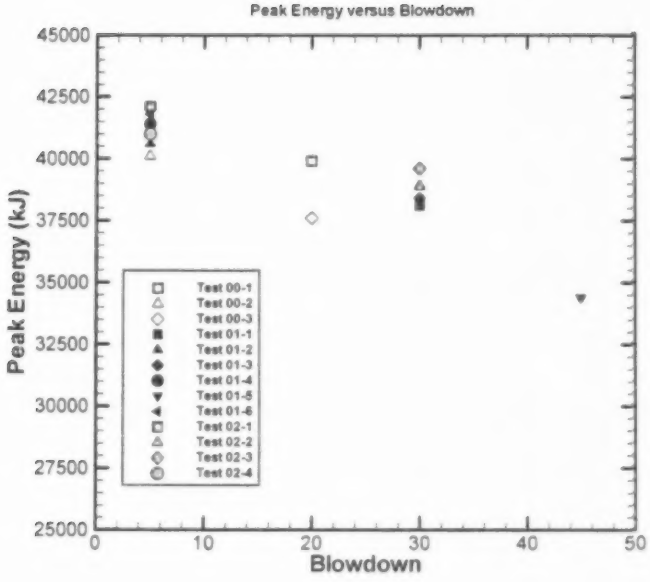
The following pages show various conditions at failure scatter plots.

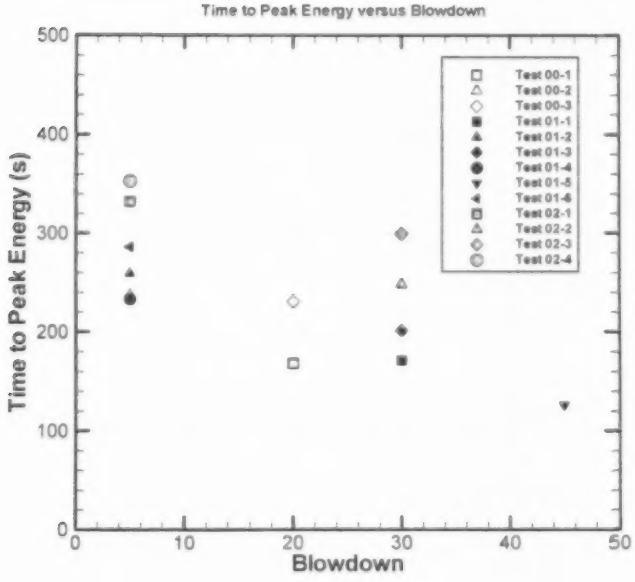

Conditions at Failure
Time versus Blowdown
Test Time (s)
Blowdown
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

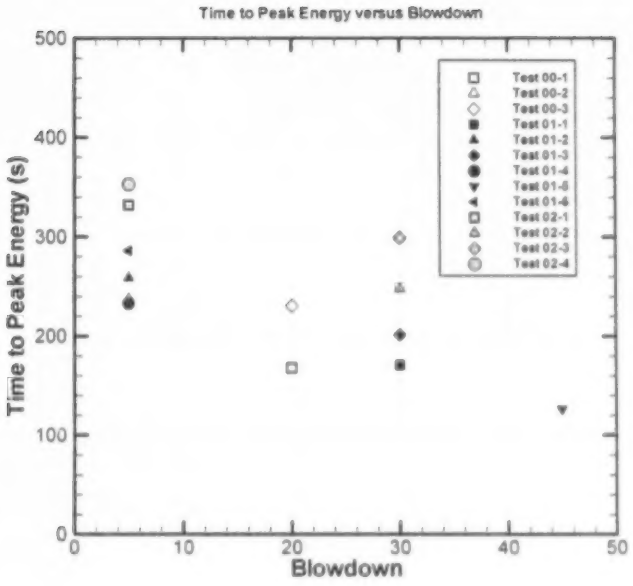

Conditions at Failure
Fill versus Blowdown
Fill (%)
Blowdown
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

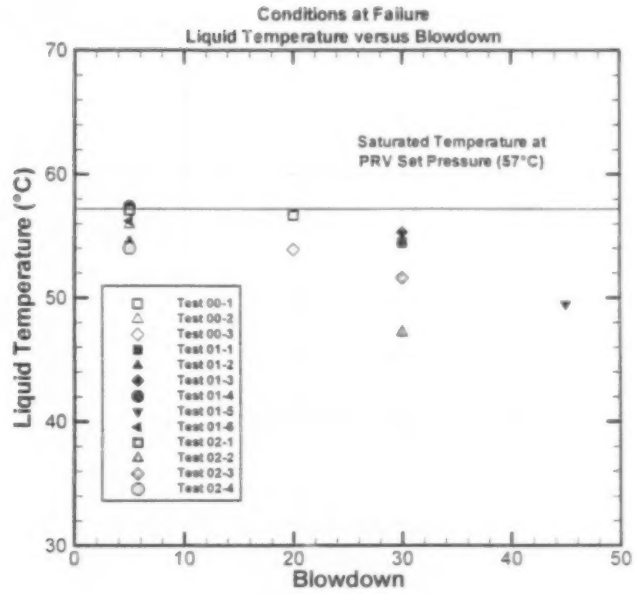

Conditions at Failure
Energy versus Blowdown
Total Energy (kJ)
Blowdown
0
10000
20000
30000
40000
50000
0
10
20
30
40
50
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

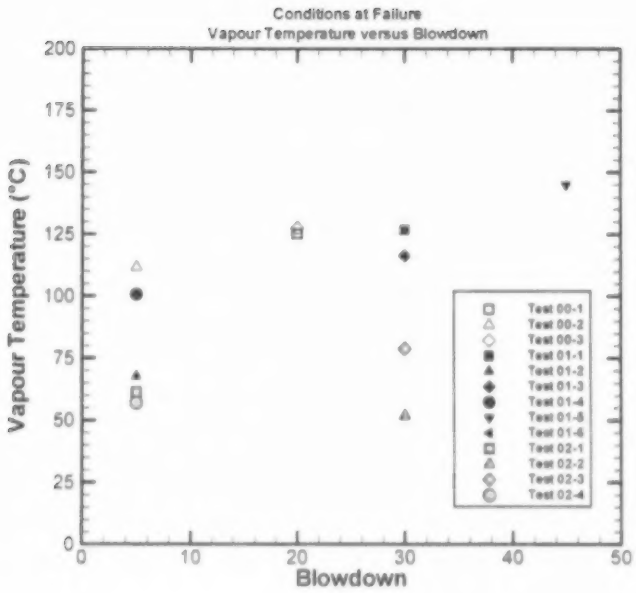

Conditions at Failure
Liquid Energy versus Blowdown
Liquid Energy (kJ)
Blowdown
0
10000
20000
30000
40000
0
10
20
30
40
50
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

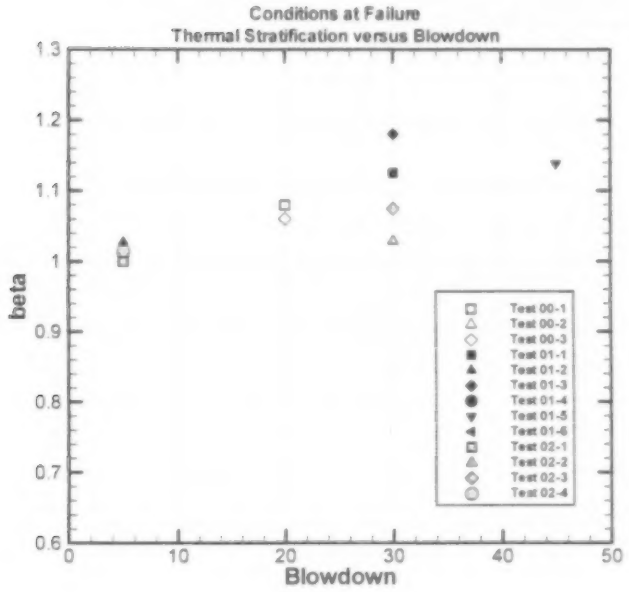

Peak Energy versus Blowdown
Peak Energy (kJ)
Blowdown
45000
42500
40000
37500
35000
32500
30000
27500
25000
0
10
20
30
40
50
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

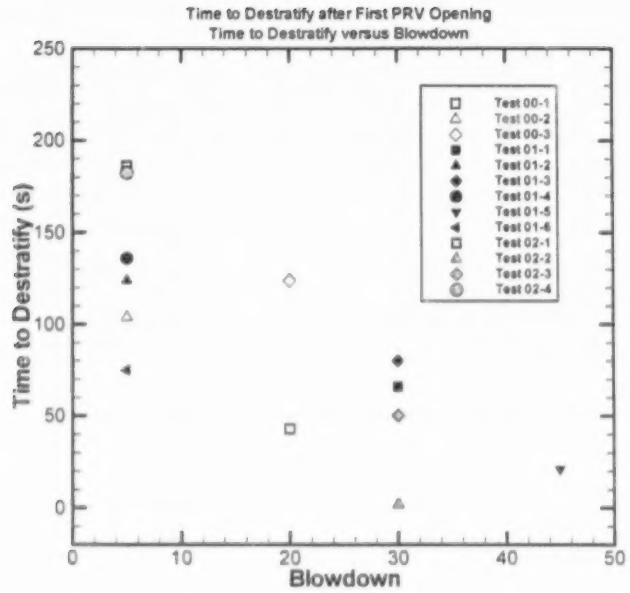

Time to Peak Energy versus Blowdown
Time to Peak Energy (s)
Blowdown
500
400
300
200
100
0
0
10
20
30
40
50
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

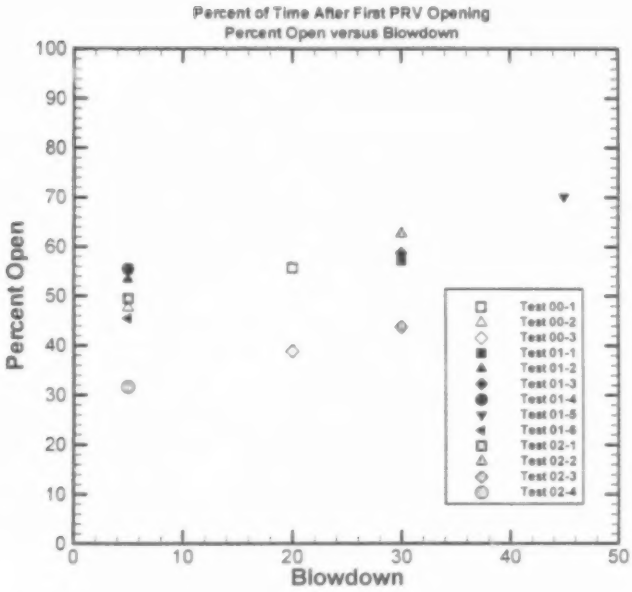

Time to Peak Energy versus Blowdown
Time to Peak Energy (s)
Blowdown
0
100
200
300
400
500
0
10
20
30
40
50
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

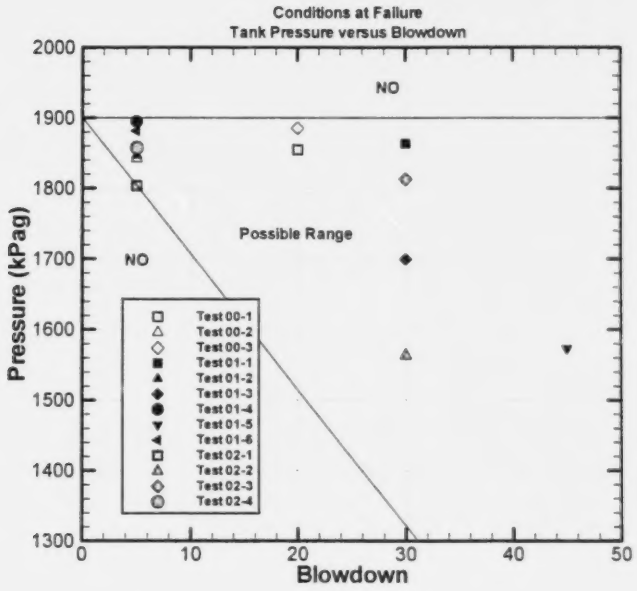

Conditions at Failure
Liquid Temperature versus Blowdown
Liquid Temperature (°C)
Blowdown
Saturated Temperature at
PRV Set Pressure (57°C)
30
40
50
60
70
0
10
20
30
40
50
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

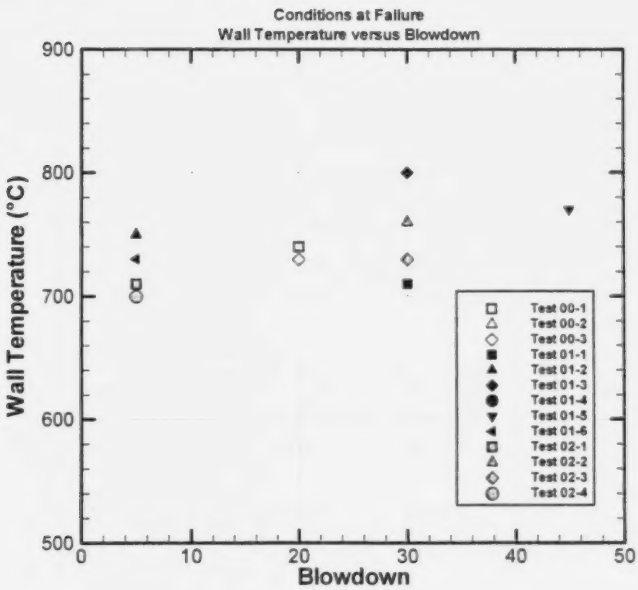

Conditions at Failure
Vapour Temperature versus Blowdown
Vapour Temperature (°C)
Blowdown
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

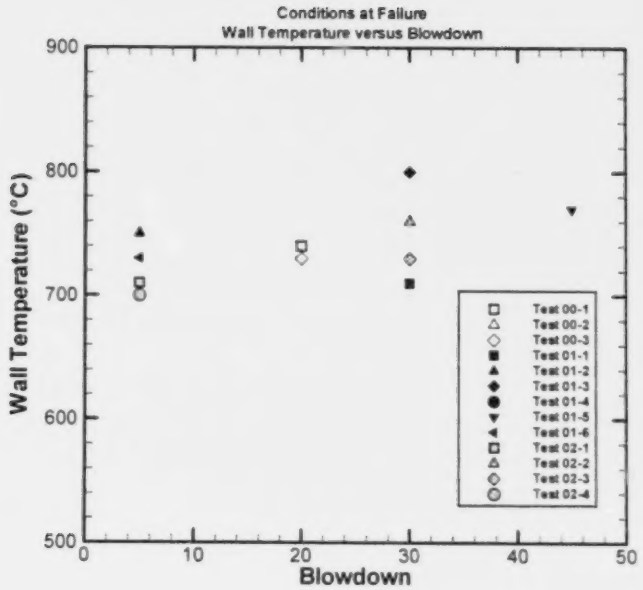

Conditions at Failure
Thermal Stratification versus Blowdown
beta
Blowdown
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

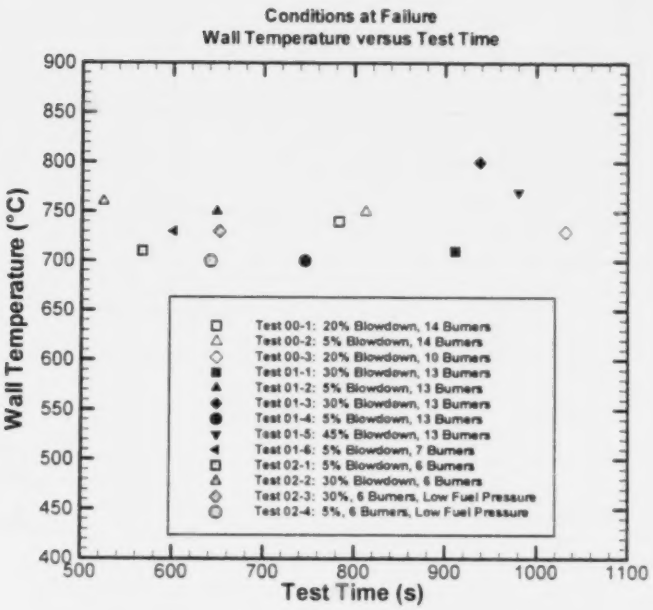

Time to Destratify after First PRV Opening
Time to Destratify versus Blowdown
Time to Destratify (s)
Blowdown
0
50
100
150
200
250
0
10
20
30
40
50
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

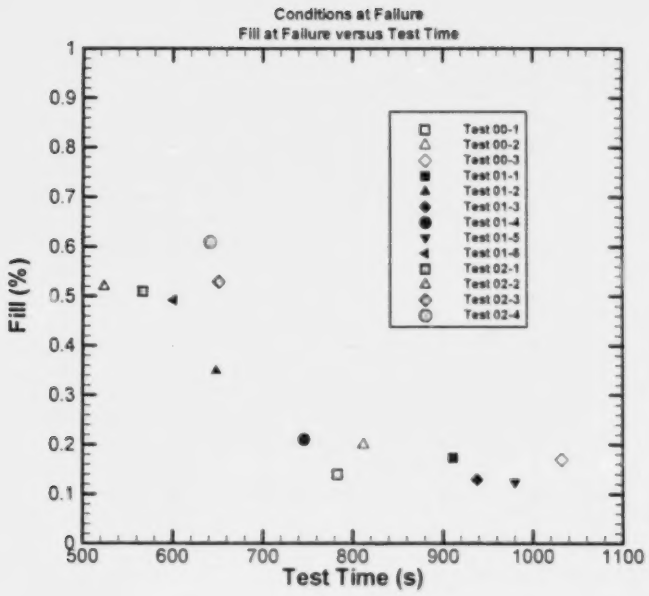

Percent of Time After First PRV Opening
Percent Open versus Blowdown
Percent Open
Blowdown
0
10
20
30
40
50
60
70
80
90
100
0
10
20
30
40
50
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

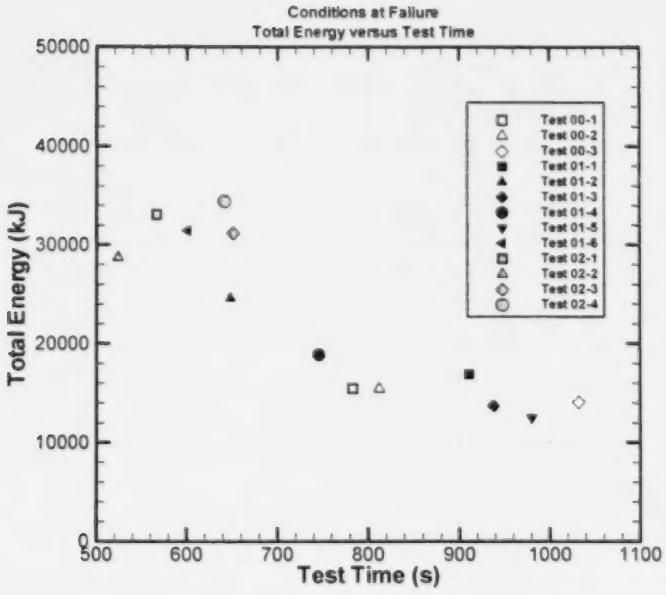

Conditions at Failure
Tank Pressure versus Blowdown
NO
Possible Range
NO
Pressure (kPag)
Blowdown
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

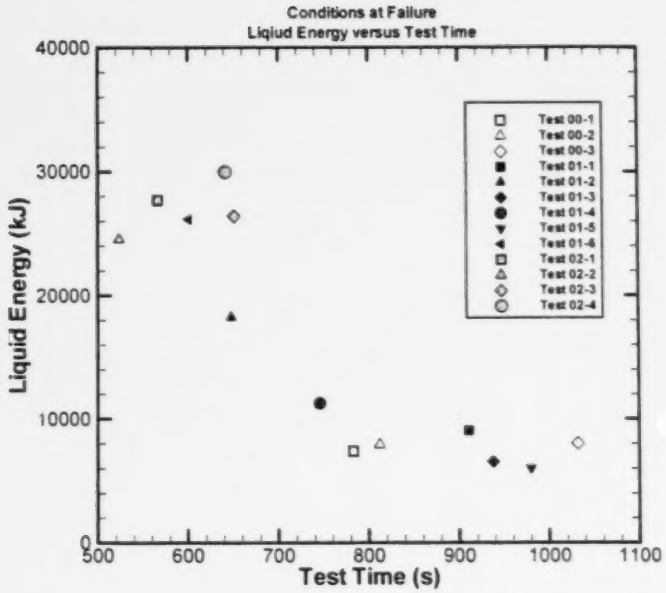

Conditions at Failure
Wall Temperature versus Blowdown
Wall Temperature (°C)
Blowdown
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

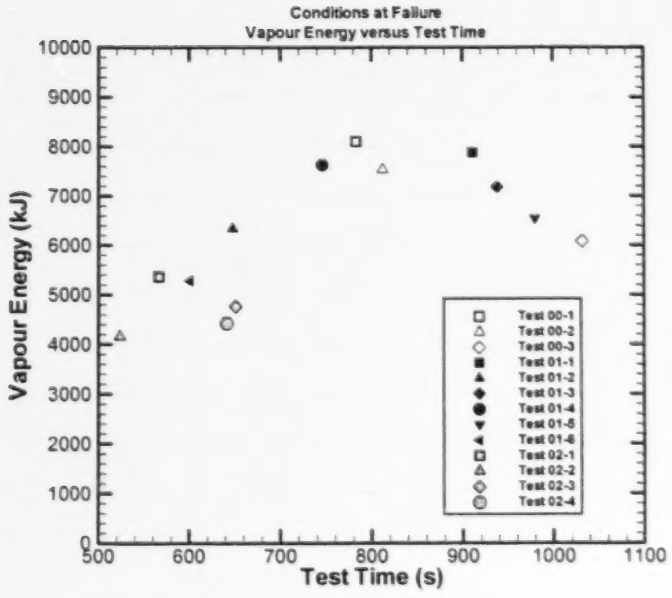

Conditions at Failure
Wall Temperature versus Blowdown
Wall Temperature (°C)
Blowdown
900
800
700
600
500
0
10
20
30
40
50
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

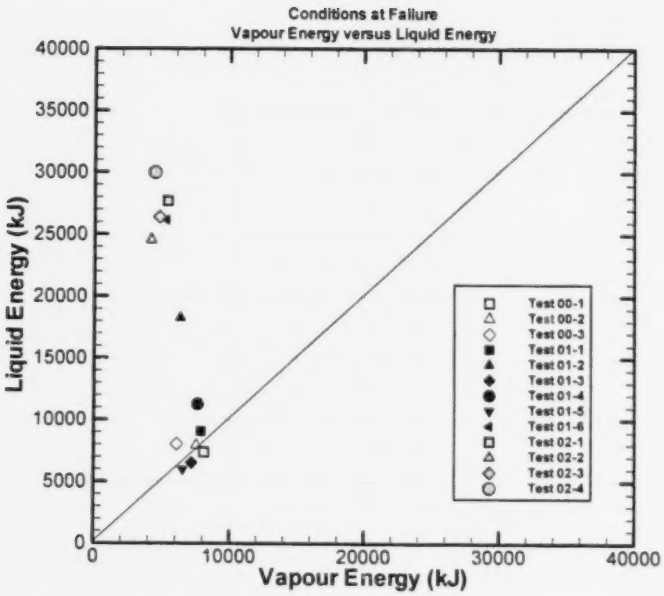

Conditions at Failure
Wall Temperature versus Test Time
Wall Temperature (°C)
Test Time (s)
900
850
800
750
700
650
600
550
500
450
400
500
600
700
800
900
1000
1100
Test 00-1: 20% Blowdown, 14 Burners
Test 00-2: 5% Blowdown, 14 Burners
Test 00-3: 20% Blowdown, 10 Burners
Test 01-1: 30% Blowdown, 13 Burners
Test 01-2: 5% Blowdown, 13 Burners
Test 01-3: 30% Blowdown, 13 Burners
Test 01-4: 5% Blowdown, 13 Burners
Test 01-5: 45% Blowdown, 13 Burners
Test 01-6: 5% Blowdown, 7 Burners
Test 02-1: 5% Blowdown, 6 Burners
Test 02-2: 30% Blowdown, 6 Burners
Test 02-3: 30%, 6 Burners, Low Fuel Pressure
Test 02-4: 5%, 6 Burners, Low Fuel Pressure

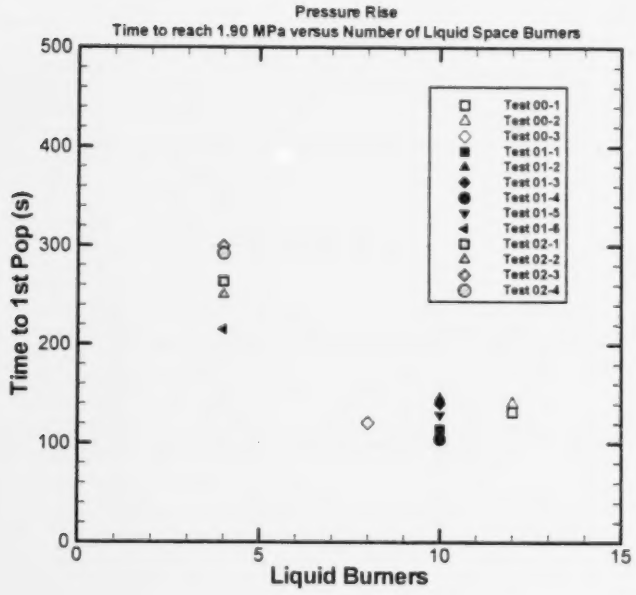

Conditions at Failure
Fill at Failure versus Test Time
Fill (%)
Test Time (s)
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

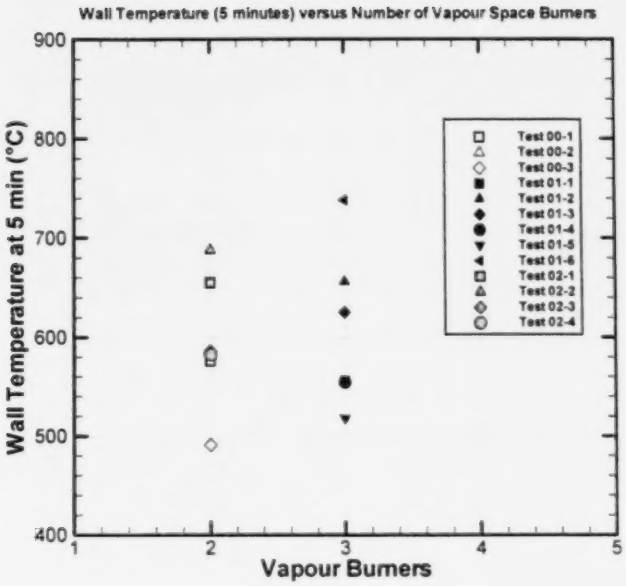

Conditions at Failure
Total Energy versus Test Time
Total Energy (kJ)
Test Time (s)
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

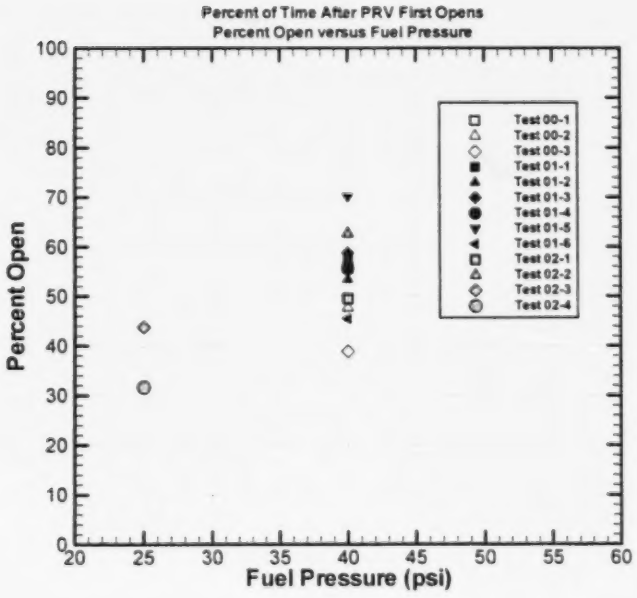

Conditions at Failure
Liqiud Energy versus Test Time
Liquid Energy (kJ)
Test Time (s)
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

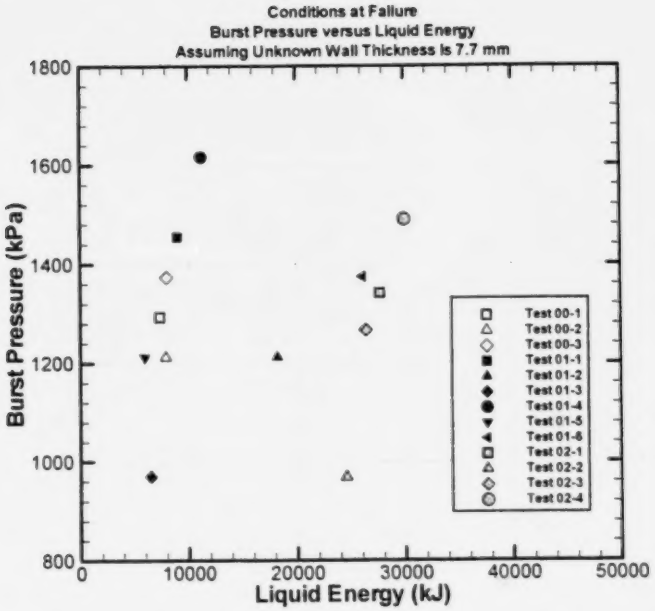

Conditions at Failure
Vapour Energy versus Test Time
Vapour Energy (kJ)
Test Time (s)
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4


Conditions at Failure
Vapour Energy versus Liquid Energy
Liquid Energy (kJ)
Vapour Energy (kJ)
0
5000
10000
15000
20000
25000
30000
35000
40000
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4


Pressure Rise
Time to reach 1.90 MPa versus Number of Liquid Space Burners
Time to 1st Pop (s)
Liquid Burners
0
100
200
300
400
500
5
10
15
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

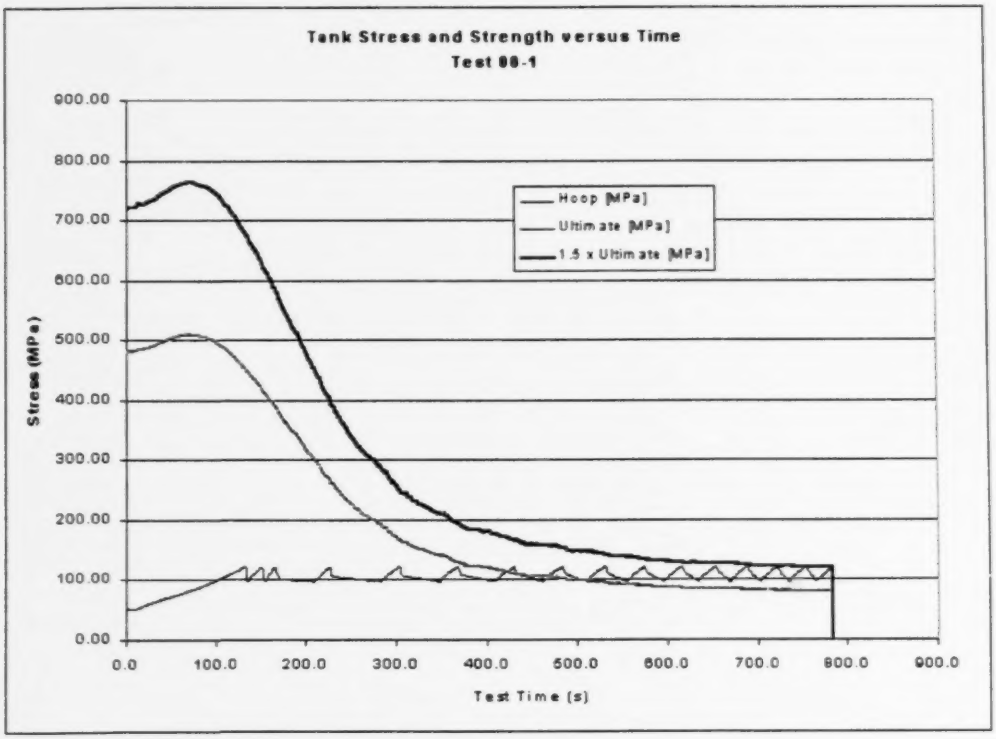

Wall Temperature (5 minutes) versus Number of Vapour Space Burners
Wall Temperature at 5 min (°C)
Vapour Burners
900
800
700
600
500
400
1
2
3
4
5
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

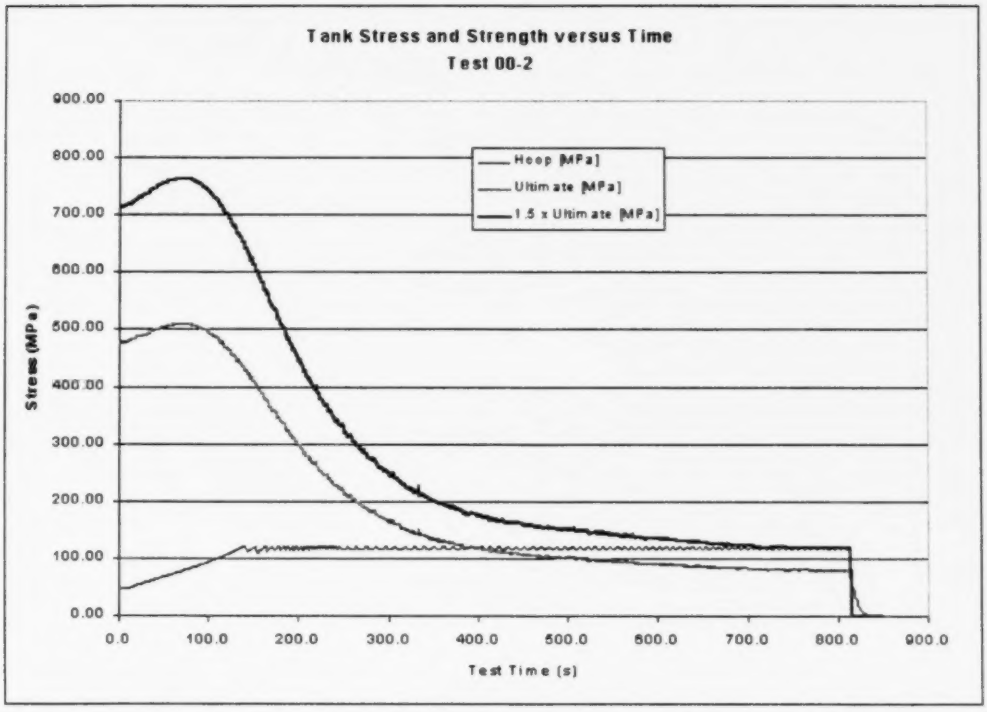

Percent of Time After PRV First Opens
Percent Open versus Fuel Pressure
Percent Open
Fuel Pressure (psi)
100
90
80
70
60
50
40
30
20
10
0
20
25
30
35
40
45
50
55
60
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

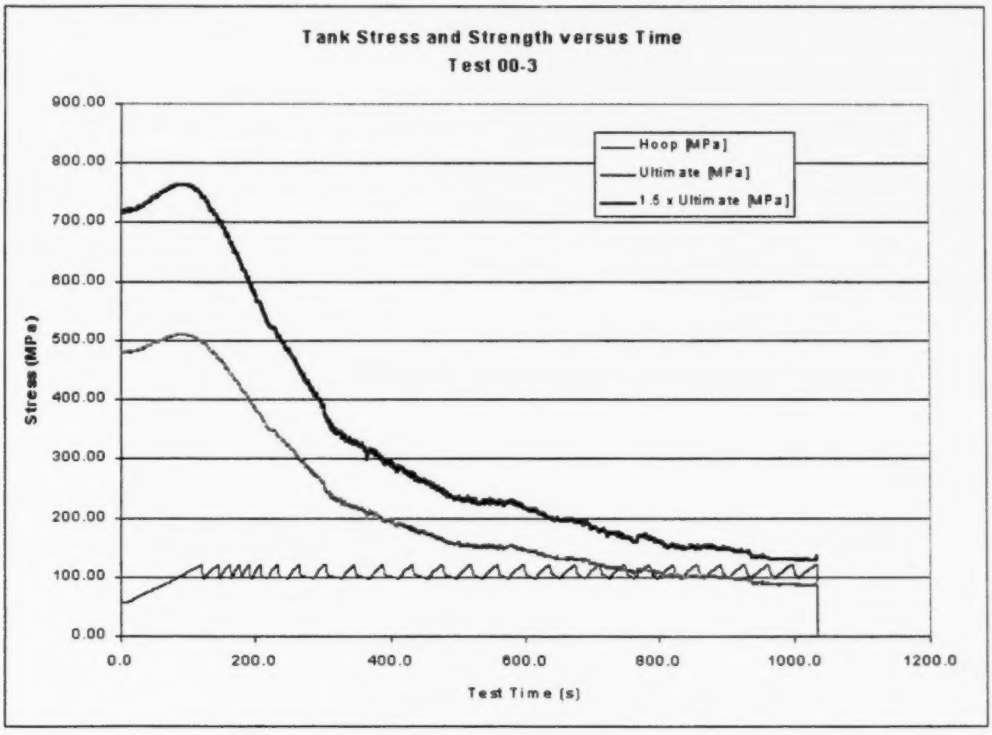

Conditions at Failure
Burst Pressure versus Liquid Energy
Assuming Unknown Wall Thickness is 7.7 mm
Burst Pressure (kPa)
1800
1600
1400
1200
1000
800
0
10000
20000
30000
40000
50000
Liquid Energy (kJ)
Test 00-1
Test 00-2
Test 00-3
Test 01-1
Test 01-2
Test 01-3
Test 01-4
Test 01-5
Test 01-6
Test 02-1
Test 02-2
Test 02-3
Test 02-4

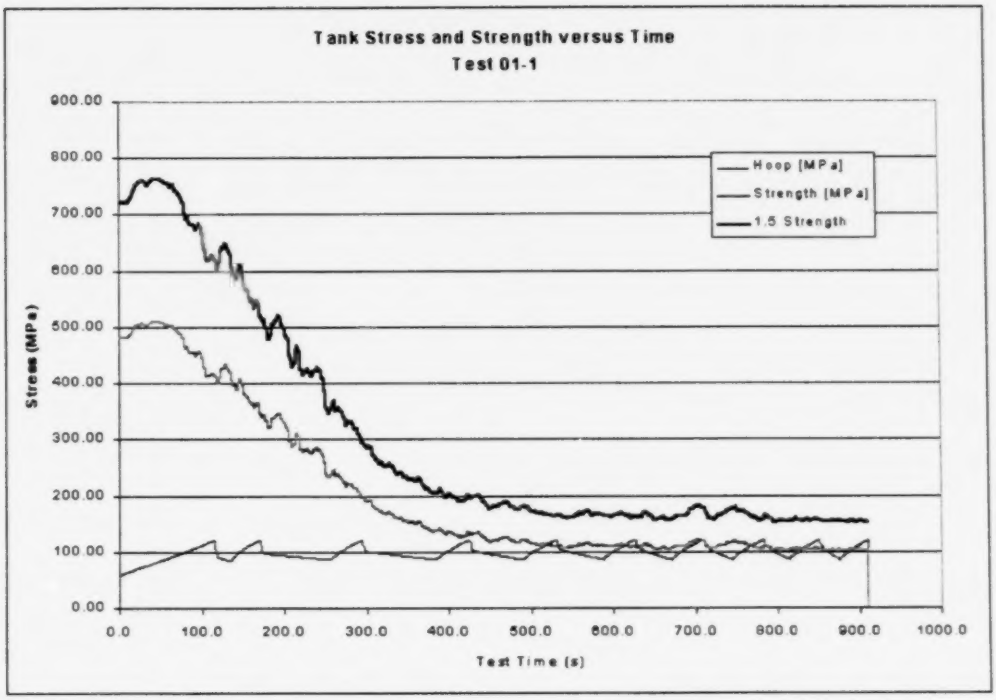
Appendix G: Failure Analysis

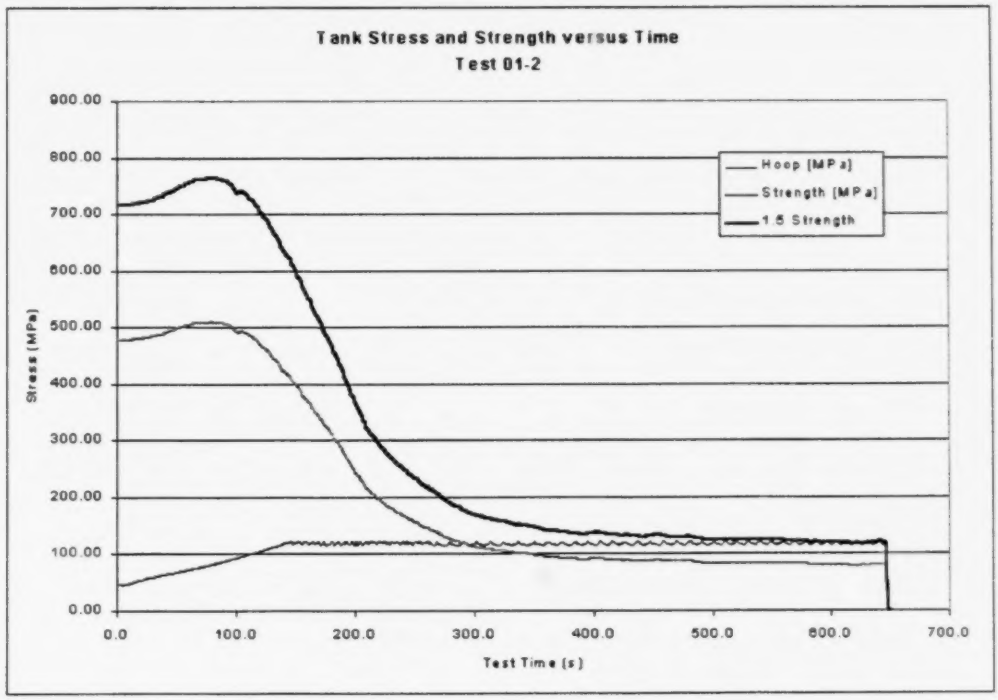
The following plots show the hoop stress and the tank strength versus time for all 13 tests. There are also some summary and comparison plots. The hoop stress is compared to both the ultimate stress and 1.5 times the ultimate stress.

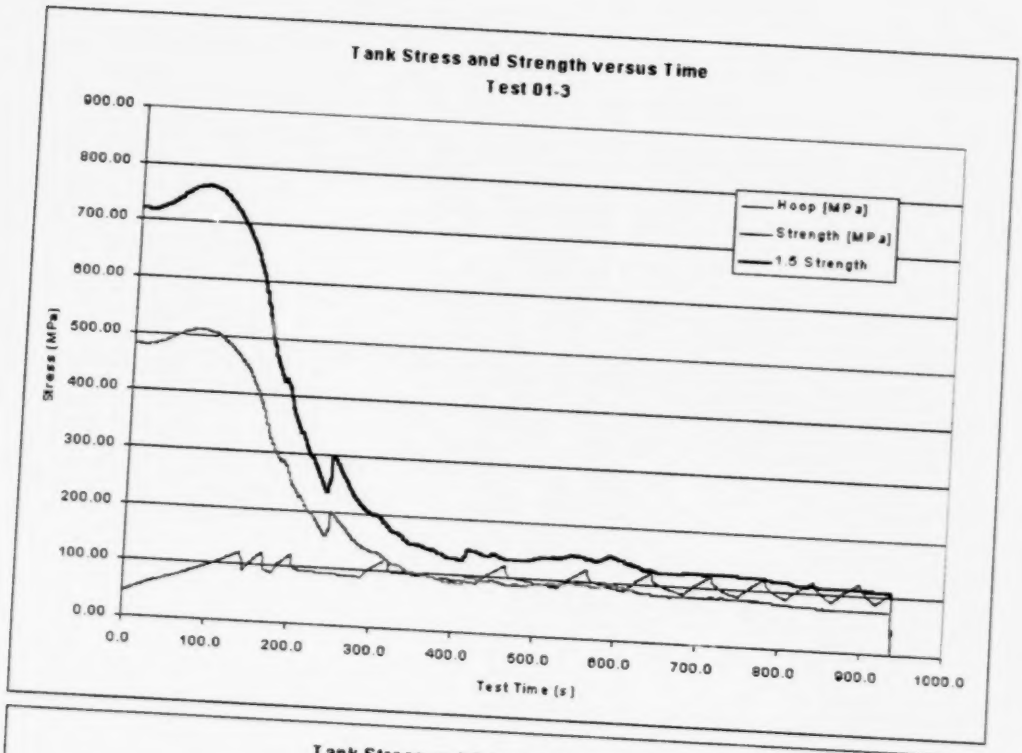


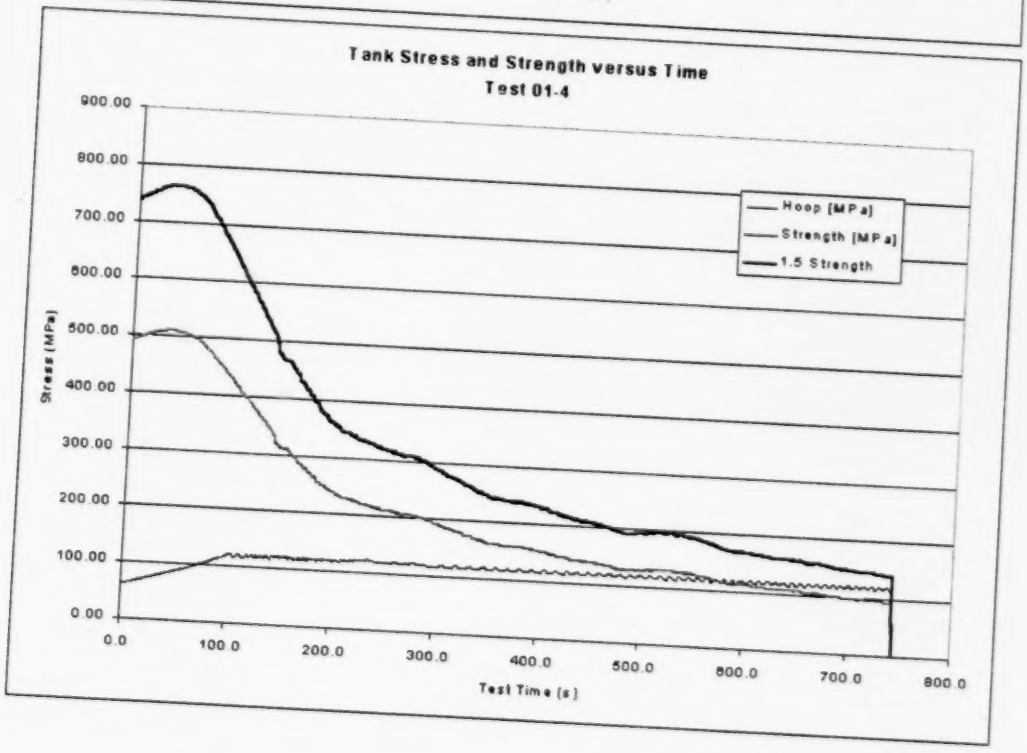

Tank Stress and Strength versus Time
Test 00-2
Hoop [MPa]
Ultimate [MPa]
1.5 x Ultimate [MPa]
Stress (MPa)
Test Time (s)
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0

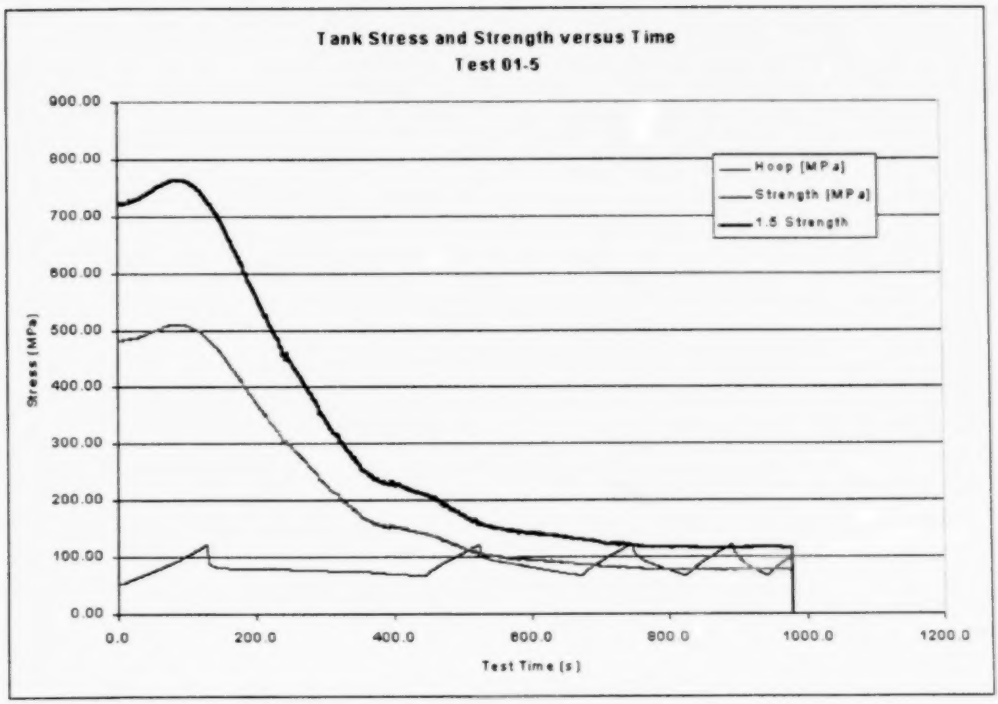

Tank Stress and Strength versus Time
Test 00-3
Hoop [MPa]
Ultimate [MPa]
1.5 x Ultimate [MPa]
Stress (MPa)
Test Time (s)
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0

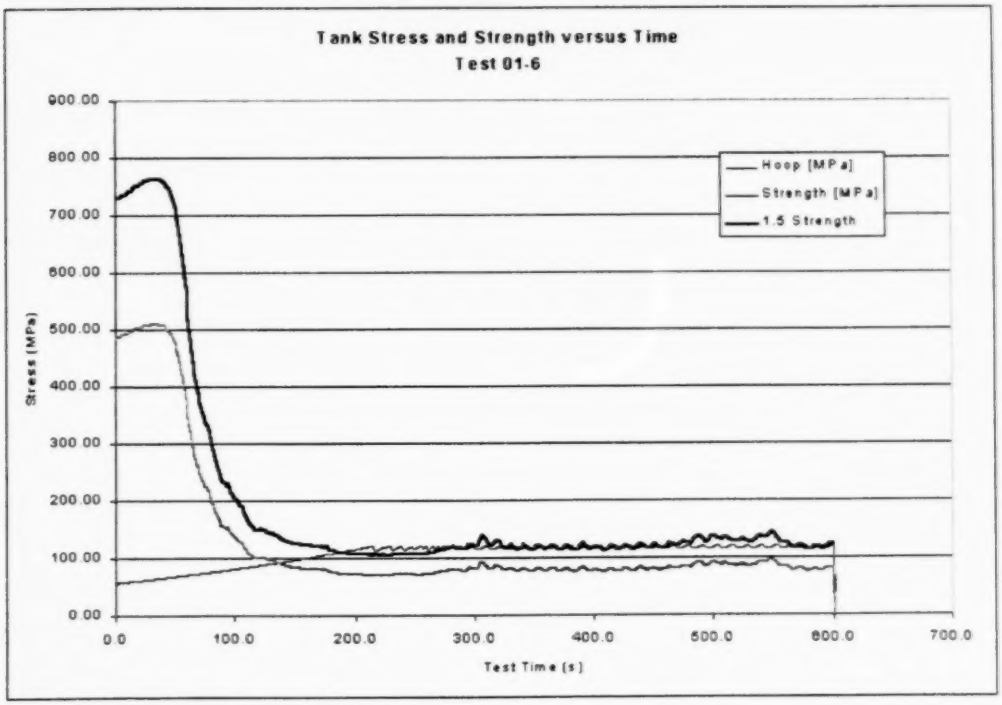

Tank Stress and Strength versus Time
Test 01-1
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Stress (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
Test Time (s)
Hoop [MPa]
Strength [MPa]
1.5 Strength

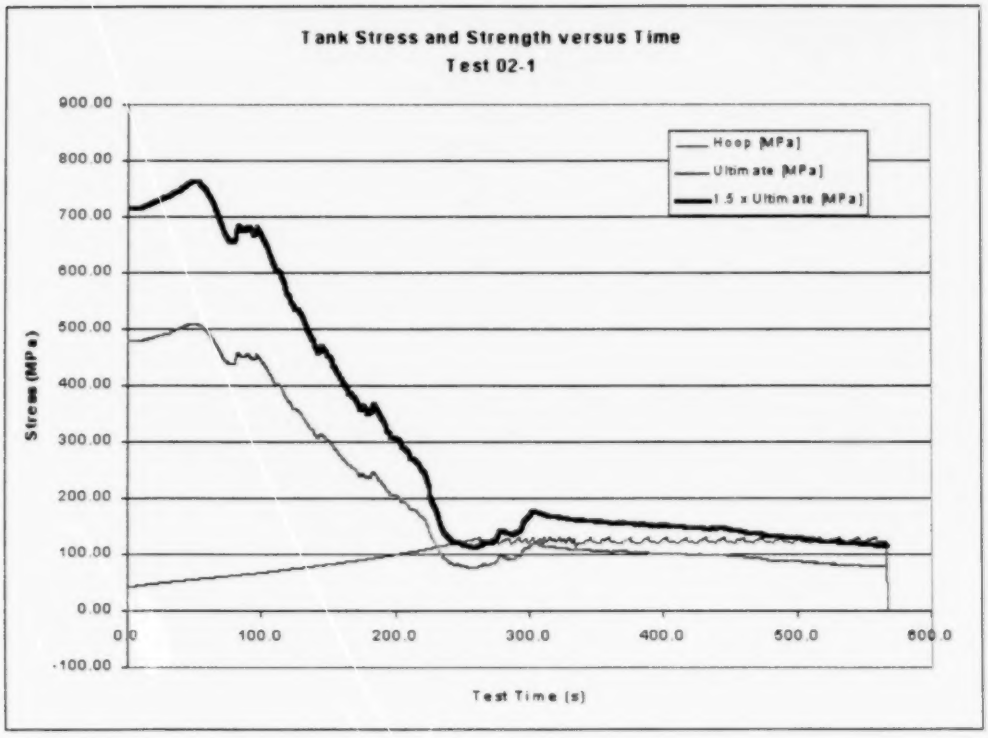

Tank Stress and Strength versus Time
Test 01-2
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Stress (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
Test Time (s)
Hoop [MPa]
Strength [MPa]
1.5 Strength

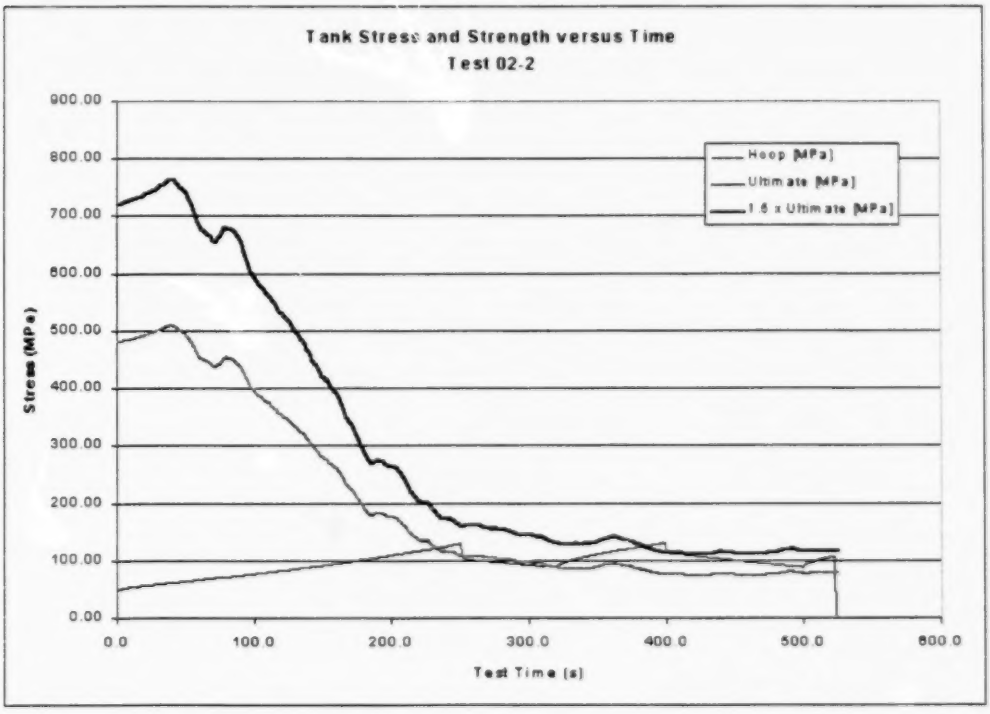

Tank Stress and Strength versus Time
Test 01-3
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Stress (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
Test Time (s)
Hoop [MPa]
Strength [MPa]
1.5 Strength

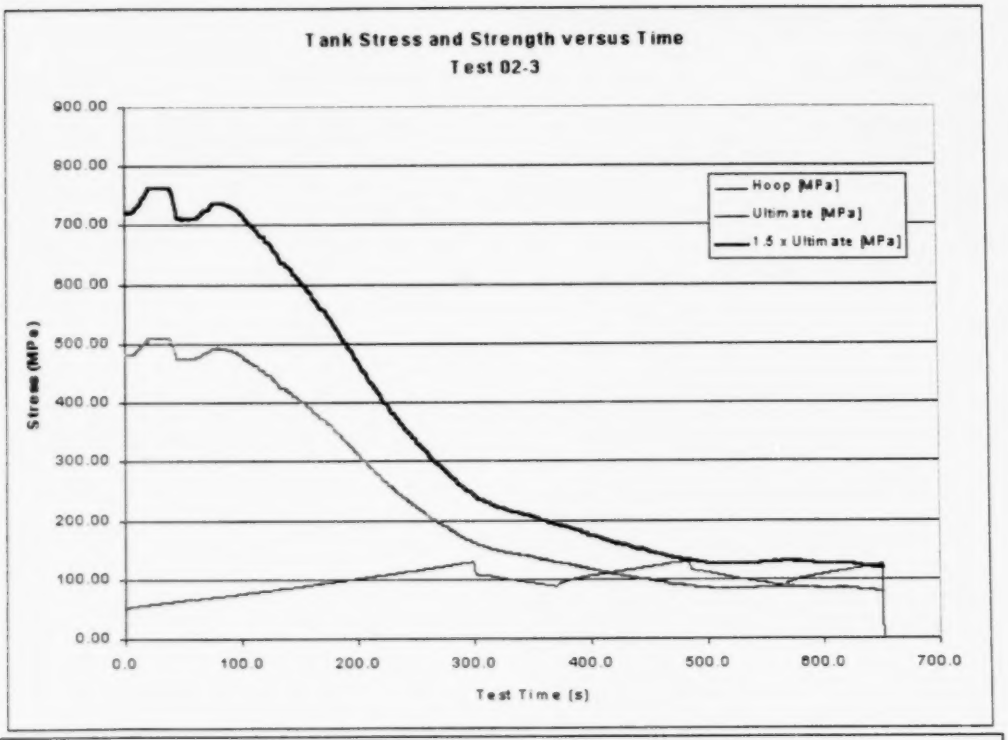

Tank Stress and Strength versus Time
Test 01-4
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Stress (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
Test Time (s)
Hoop [MPa]
Strength [MPa]
1.5 Strength

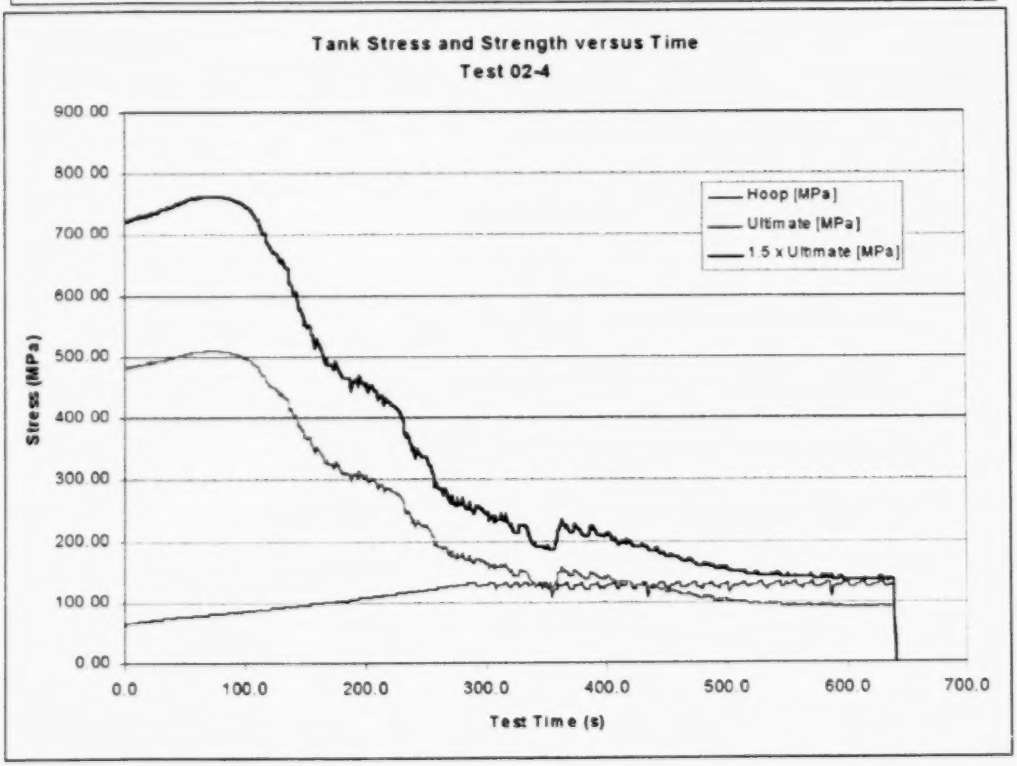

Tank Stress and Strength versus Time
Test 01-5
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Stress (MPa)
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
Test Time (s)
Hoop (MPa)
Strength (MPa)
1.5 Strength

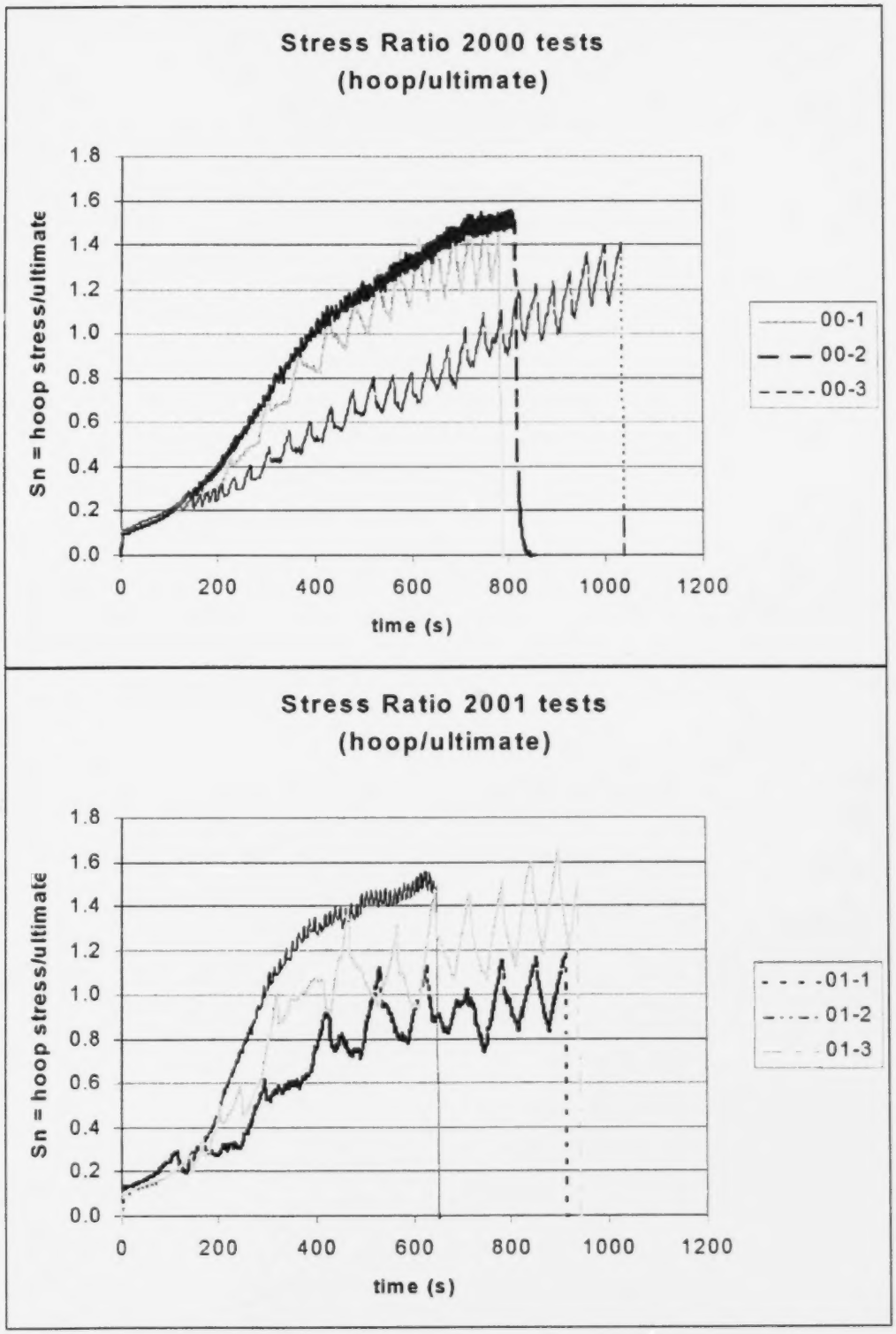

Tank Stress and Strength versus Time
Test 01-6
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Stress (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
Test Time (s)
Hoop (MPa)
Strength (MPa)
1.5 Strength

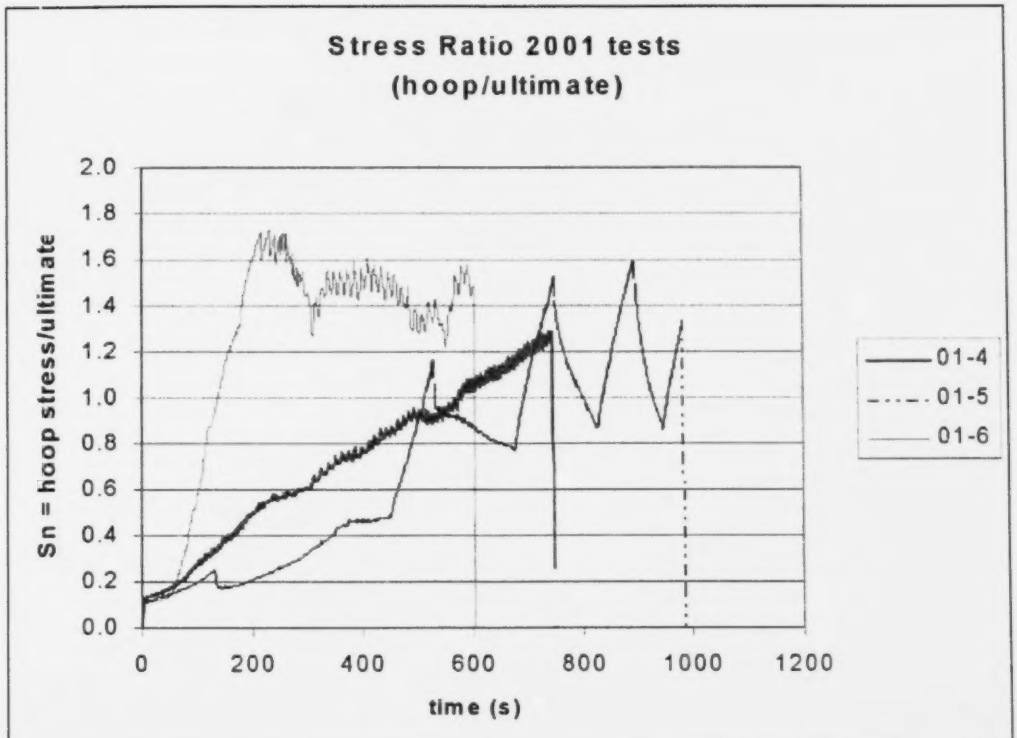

Tank Stress and Strength versus Time
Test 02-1
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
-100.00
Stress (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
Test Time (s)
Hoop [MPa]
Ultimate [MPa]
1.5 x Ultimate [MPa]

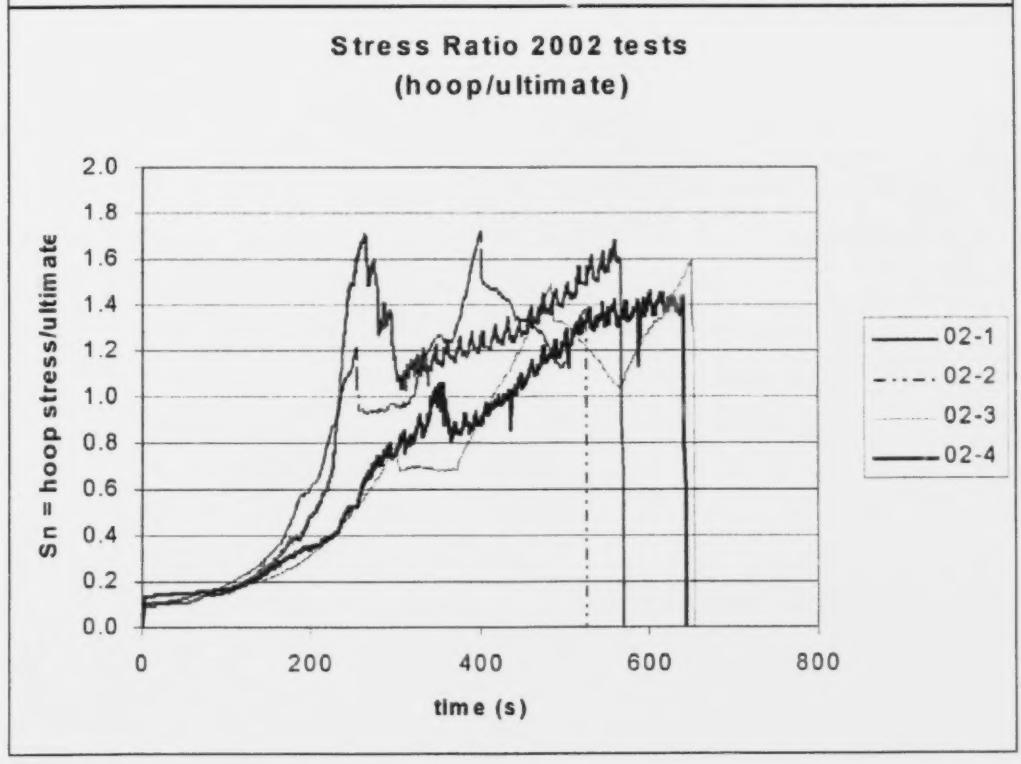

Tank Stress and Strength versus Time
Test 02-2
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Stress (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
Test Time (s)
Hoop [MPa]
Ultimate [MPa]
1.5 x Ultimate [MPa]

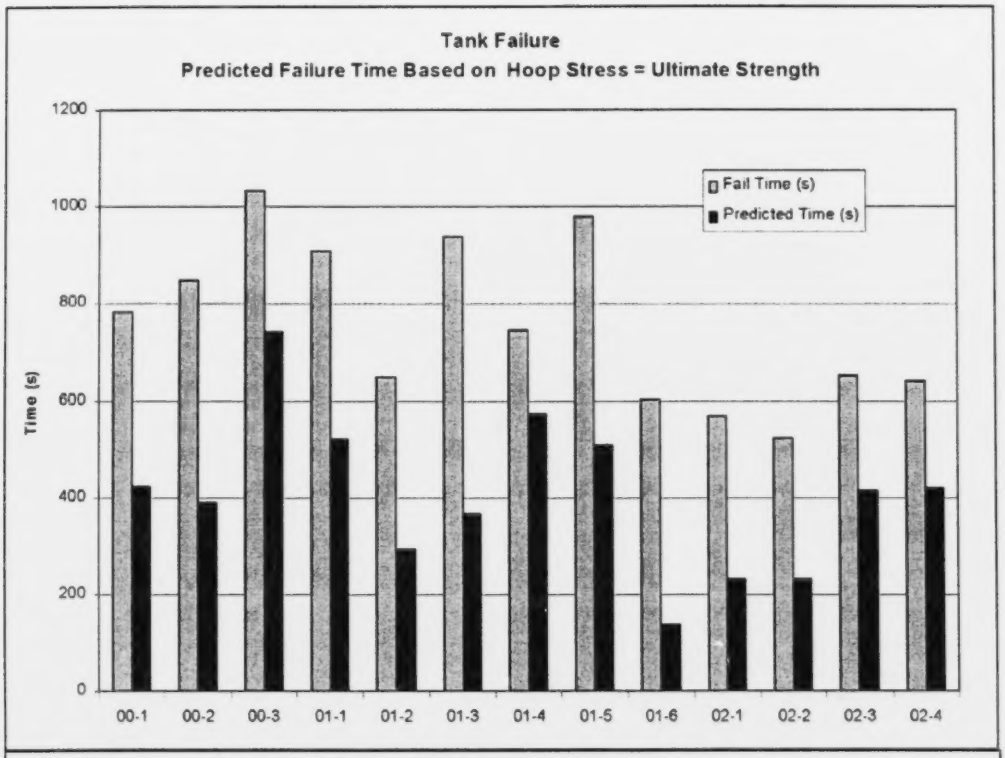

Tank Stress and Strength versus Time
Test 02-3
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Stress (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
Test Time (s)
Hoop [MPa]
Ultimate [MPa]
1.5 x Ultimate [MPa]

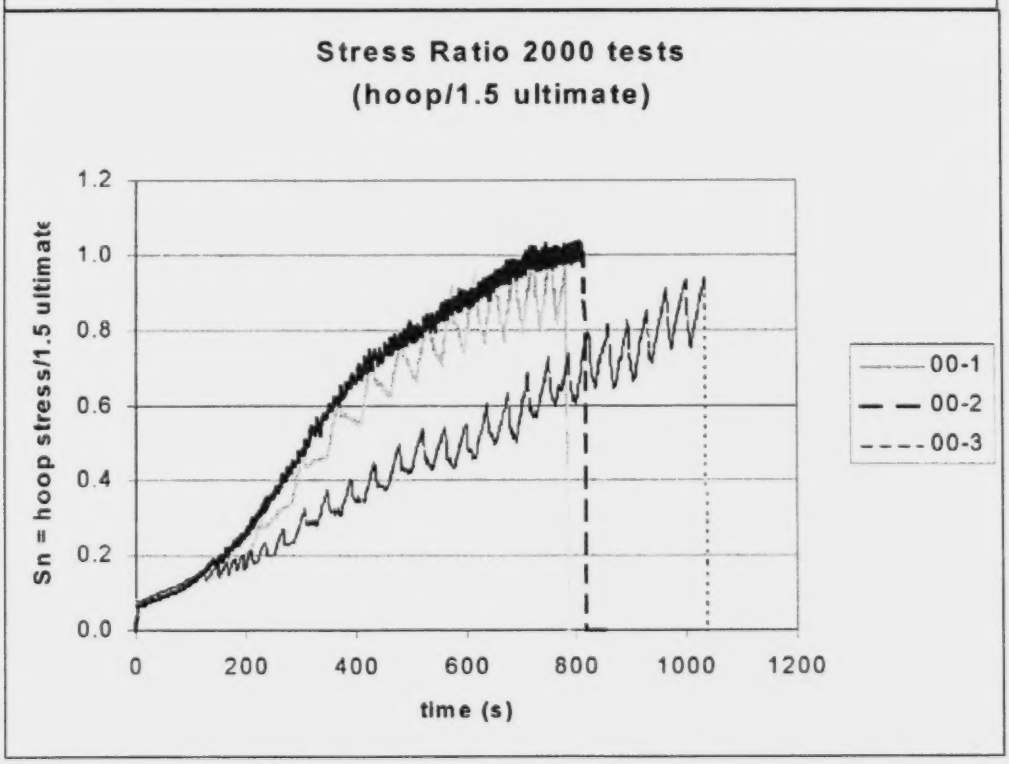

Tank Stress and Strength versus Time
Test 02-4
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Stress (MPa)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
Test Time (s)
Hoop [MPa]
Ultimate [MPa]
1.5 x Ultimate [MPa]

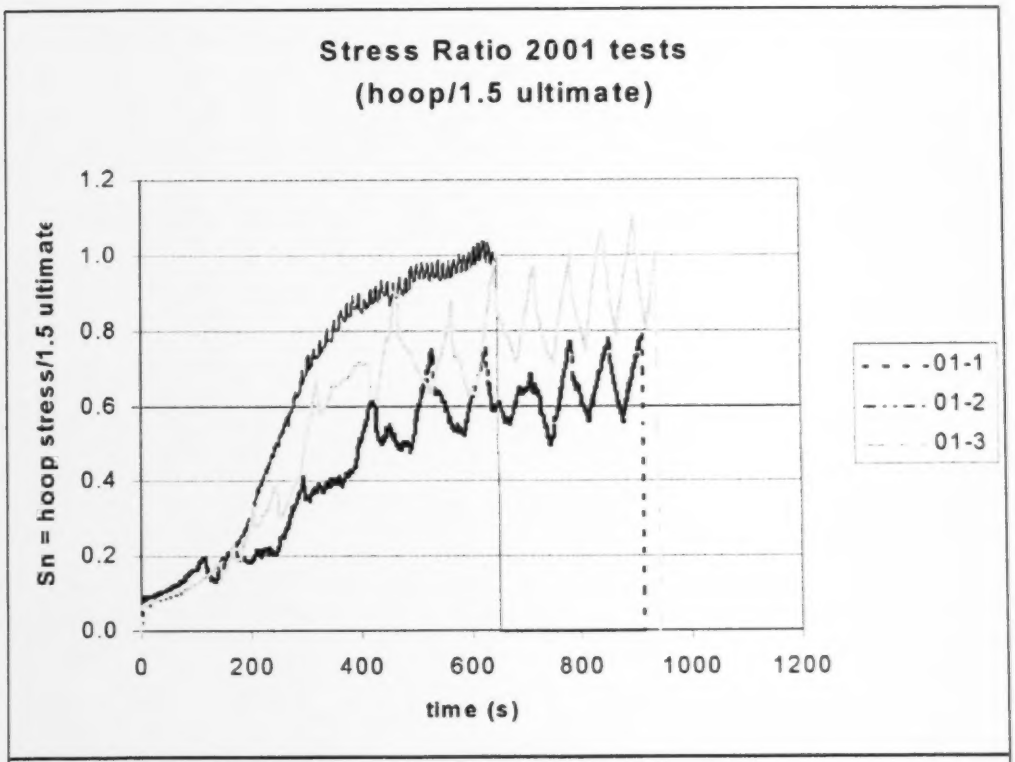

Stress Ratio 2000 tests
(hoop/ultimate)
Sn = hoop stress/ultimate
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
1200
time (s)
00-1
00-2
00-3
Stress Ratio 2001 tests
(hoop/ultimate)
Sn = hoop stress/ultimate
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
1200
time (s)
01-1
01-2
01-3

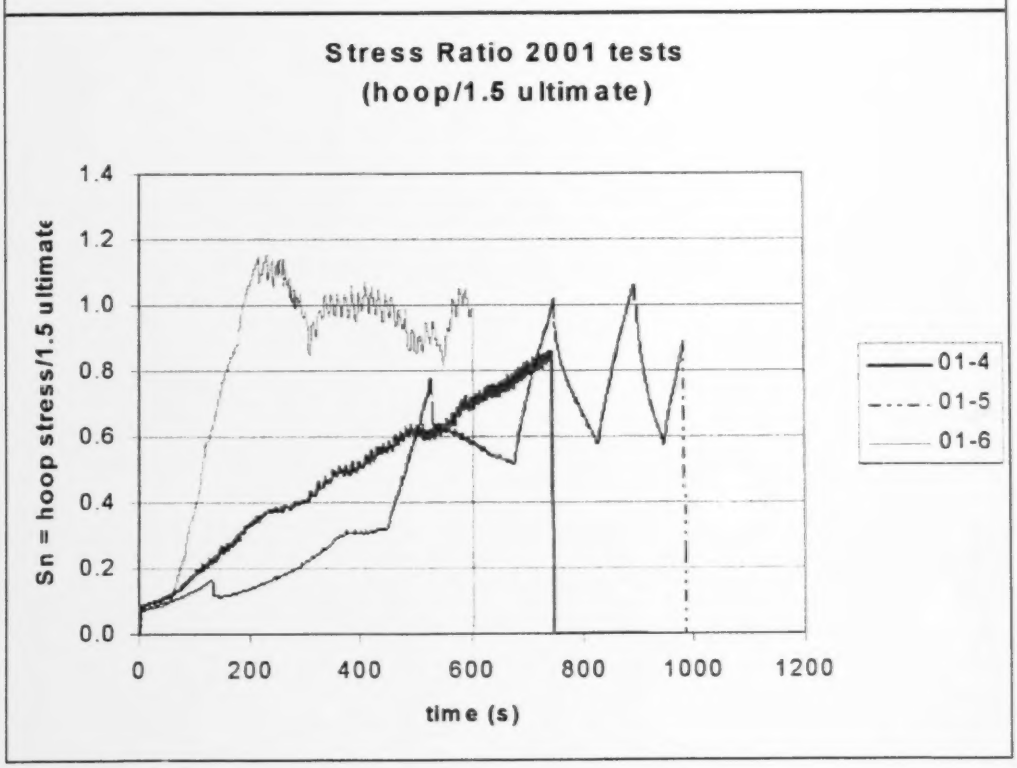

Stress Ratio 2001 tests
(hoop/ultimate)
Sn = hoop stress/ultimate
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
1200
time (s)
01-4
01-5
01-6

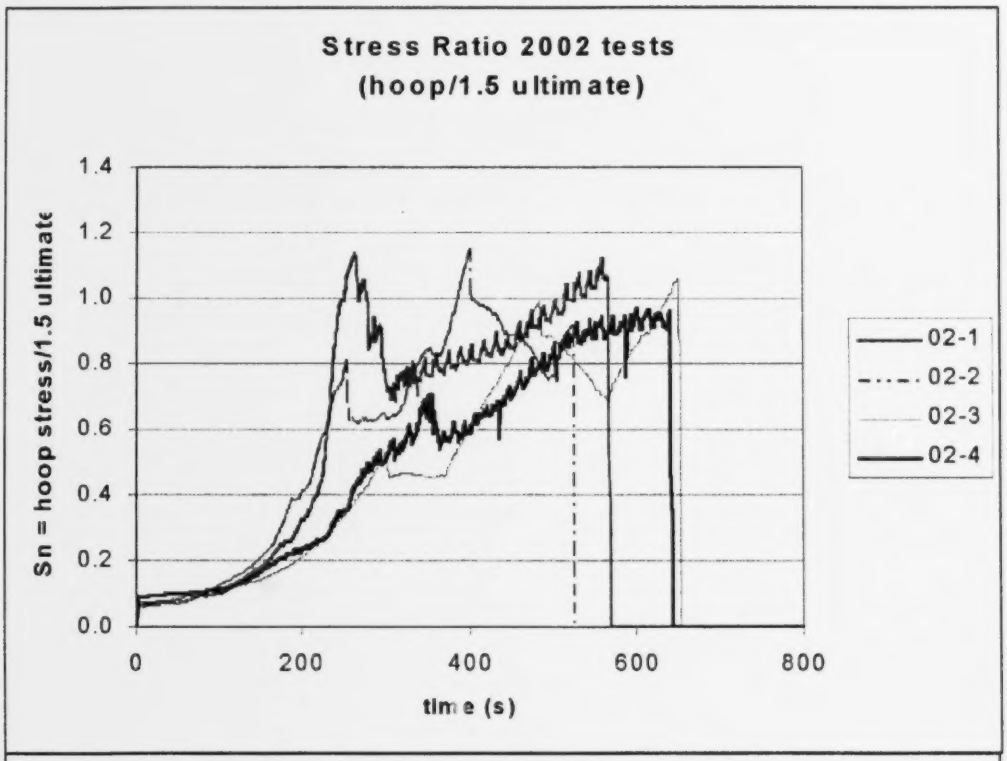

Stress Ratio 2002 tests
(hoop/ultimate)
Sn = hoop stress/ultimate
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
time (s)
02-1
02-2
02-3
02-4

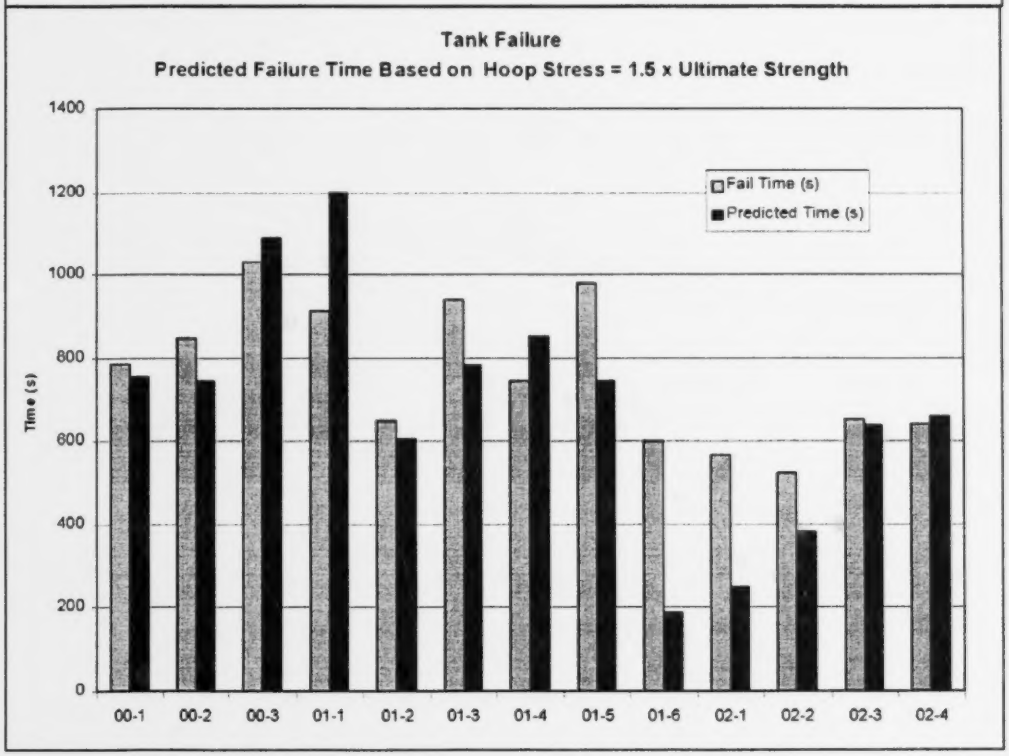

Tank Failure
Predicted Failure Time Based on Hoop Stress = Ultimate Strength
Time (s)
0
200
400
600
800
1000
1200
Fail Time (s)
Predicted Time (s)
00-1
00-2
00-3
01-1
01-2
01-3
01-4
01-5
01-6
02-1
02-2
02-3
02-4

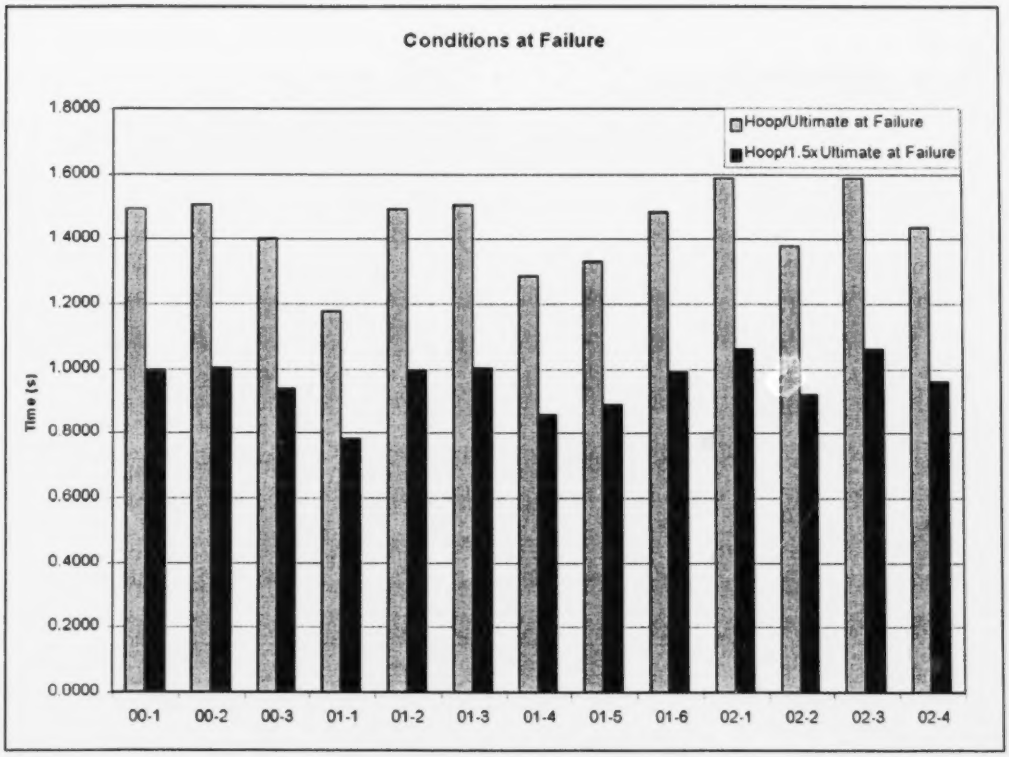

Stress Ratio 2000 tests
(hoop/1.5 ultimate)
Sn = hoop stress/1.5 ultimate
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
200
400
600
800
1000
1200
time (s)
00-1
00-2
00-3


Stress Ratio 2001 tests
(hoop/1.5 ultimate)
Sn = hoop stress/1.5 ultimate
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
1200
time (s)
01-1
01-2
01-3


Stress Ratio 2001 tests
(hoop/1.5 ultimate)
Sn = hoop stress/1.5 ultimate
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
1200
time (s)
01-4
01-5
01-6


Stress Ratio 2002 tests
(hoop/1.5 ultimate)
Sn = hoop stress/1.5 ultimate
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
time (s)
02-1
02-2
02-3
02-4


Tank Failure
Predicted Failure Time Based on Hoop Stress = 1.5 x Ultimate Strength
Time (s)
1400
1200
1000
800
600
400
200
0
Fail Time (s)
Predicted Time (s)
00-1
00-2
00-3
01-1
01-2
01-3
01-4
01-5
01-6
02-1
02-2
02-3
02-4


Conditions at Failure
Hoop/Ultimate at Failure
Hoop/1.5x Ultimate at Failure
Time (s)
1.8000
1.6000
1.4000
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
00-1
00-2
00-3
01-1
01-2
01-3
01-4
01-5
01-6
02-1
02-2
02-3
02-4

Appendix H: Error Analysis

There were two sources of error observed in the tests:

- errors associated with the accuracy of the instruments
- errors associated with the instrument installation

The following table summarizes the errors associated with the instruments, while subsections below discuss installation errors. The errors associated with the instruments were in acceptable ranges, but in some cases, installation methods resulted in significant errors.

Measurement	Device	Accuracy
Lading Temperature	Type K Thermocouple	+/- 1°C
Tank Wall Temperature	Type K Thermocouple	+/- 1°C
Tank Pressure	Pressure Transducer	+/- 12 kPa
PRV Nozzle Pressure	Pressure Transducer	+/- 12 kPa
PRV Nozzle Temperature	Type K Thermocouple	+/- 1°C

Accuracy of Instruments

The errors can also be categorized according to relative size:
- Large, significant errors include wall temperature measurements and initial fill estimation.
- Small, less significant errors include lading pressure, lading temperature, nozzle pressure, and nozzle temperature measurements.

Wall Temperature Errors

Previous work by Birk and Cunningham (1994) was preformed to verify the accuracy of wall thermocouple readings. An instrumented piece of pressure vessel steel was exposed to a torch fire. The thermocouples were installed in a similar manner as the field tests, but without the insulation and the channel of steel. A difference of up to 100°C was seen between the steady measured temperature and the actual temperature. The most likely cause of this error is that the method of installation resulted in a large heat conduction error due to the small mass of the thermocouple and the hot fire.

Later testing (see Appendix I) showed that this conduction error could be reduced with strips of ceramic insulation and a steel jacket to hold the insulation in place. These tests reduced the error to +/- 10°C.

Lading Pressure and Temperature Errors

Temperatures and pressure within the tank were measured more accurately than the wall temperatures. Conduction errors were much smaller for lading thermocouples while pressure transducers were carefully calibrated before the tests. The average vapour and liquid temperature calculations do contain errors, however. The largest amount of uncertainty results from the difficulty in determining exactly when a thermocouple moves from the liquid to the vapour and the errors in the installed thermocouple height.

To validate the process, a manual check was done on Test 01-1. The thermocouple data file was opened into a spreadsheet and by manually inspecting the trends on a plot and comparing the temperature to the saturation temperature, it was decided when a thermocouple moved from the liquid to the vapour. The manual results were compared to the output of the program and it was seen that the two methods were comparable. The maximum difference of approximately 12°C between the two methods was seen in the average vapour temperatures. Moodie et al (1988) reported that liquid frothing and swelling made it very difficult to determine the exact location of the liquid/vapour interface in their testing.

Mass Flow Errors

The mass flow calculations depended on the measured nozzle temperature and pressure. Errors in either the measurements or calculations can result in an erroneous total mass flow and final fill at failure.

A pressure ratio between the throat pressure and the stagnation pressure of 0.59 was assumed for the calculations. This assumption was based a specific heat ratio of k=1.1. In reality, the specific heat ratio, and thus the pressure ratio depends on the nozzle temperature. The data from Test 01-3 was studied to understand the sensitivity of this parameter. For this test, given tabulated propane data and the measured nozzle temperature, the specific heat ratio ranged from 1.134 to 1.069. The following table shows that varying the pressure ratio in this range has a very little effect on the total mass flow calculation.

P_{throat}/P_{stag}	k	total mass flow	% Different
0.57	1.172	606.3 kg	-0.20%
0.58	1.122	607.0 kg	-0.07%
0.59	1.075	607.4 kg	0.00%
0.6	1.029	607.6 kg	0.02%
0.61	0.985	607.4 kg	-0.01%

Effects of Varying Nozzle Pressure Ratio on Mass Flow

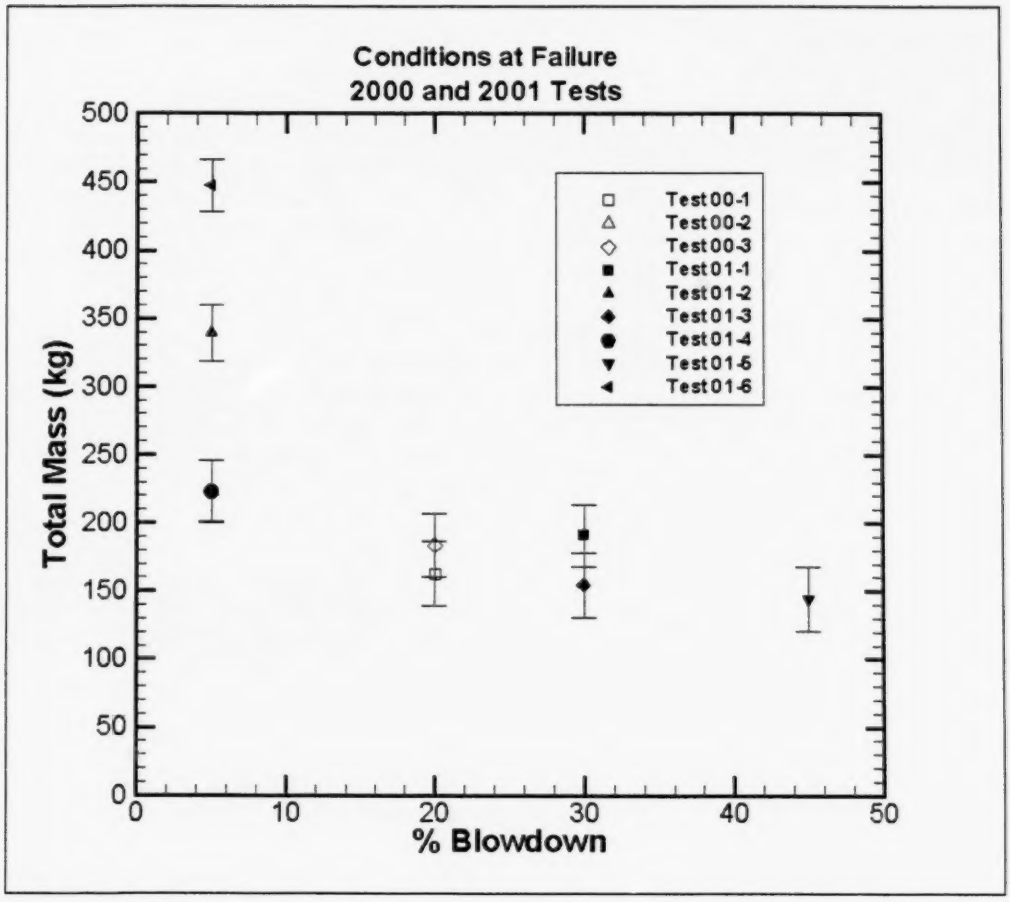
Although the errors associated with the nozzle thermocouple and pressure transducer are well within acceptable ranges, the errors can propagate through the calculations. Using the data from Test 01-3, the effect of changing the temperature, pressure, or both at the same time can be studied. The following table shows how adjusting the measured values according to the instrument's tolerance affects the final answer. The biggest error occurs when both the pressure and the temperature are off by the maximum allowable amount.

Change	total mass flow	% Different
No Change	607.5 kg	0.00%
T-->T+1°C	606.1 kg	-0.20%
T-->T-1°C	609.0 kg	0.30%
P-->P+12 kPa	612.8 kg	0.90%
P-->P-12 kPa	602.3 kg	-0.80%
P-->P+12 kPa; T-->T-1°C	614.2 kg	1.10%
P-->P-12 kPa; T-->T+1°C	600.8 kg	-1.10%

Propagation of Errors in Mass Flow Calculations

Finally, a significant source of error comes from the uncertainty in the initial volume and mass of propane. It is estimated that the initial volume of the liquid propane in the tank after purging is +/- 10 litres. This corresponds to a mass of +/- 5.0 kg assuming the liquid propane was at 20°C.

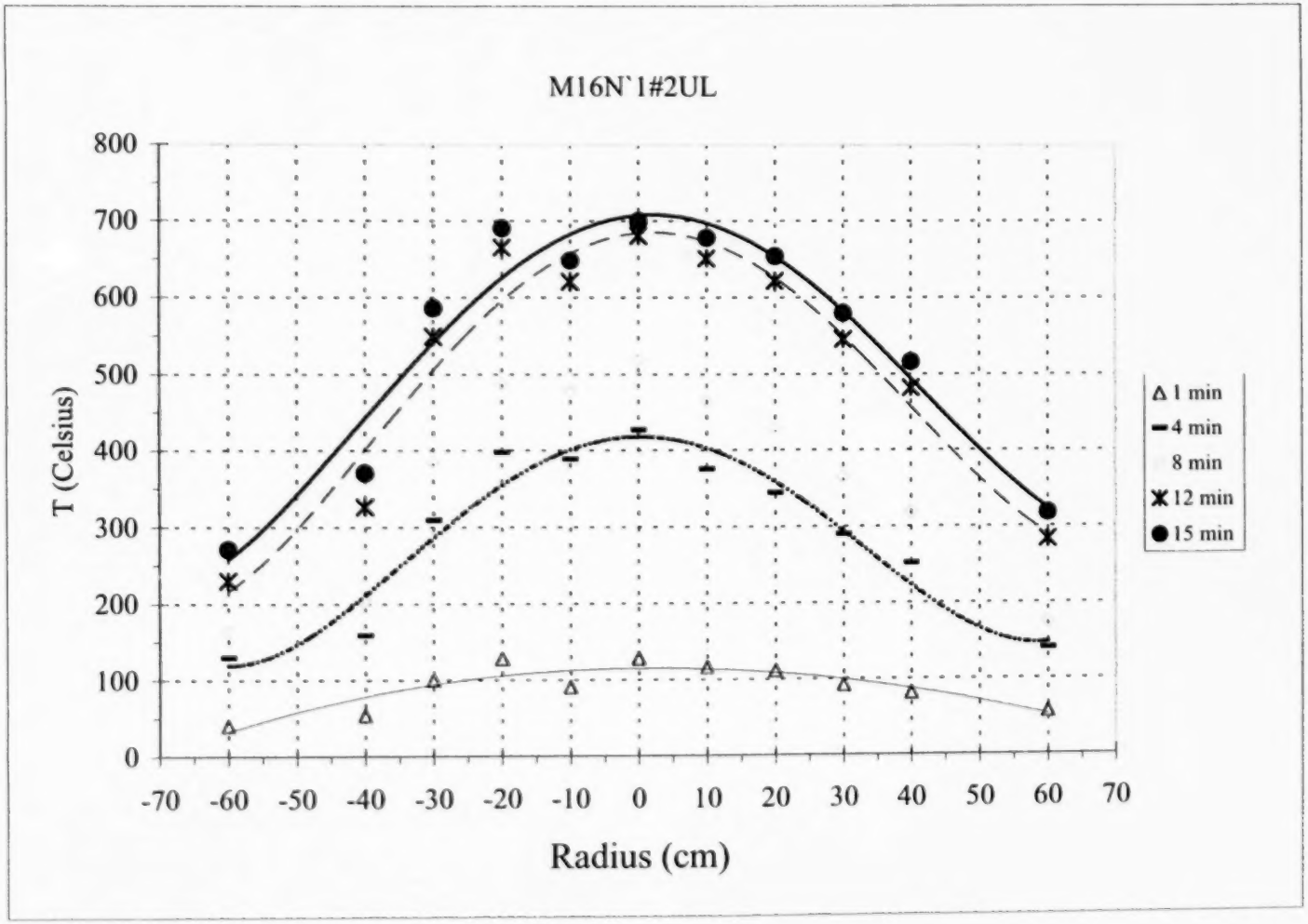
The summation of the error due to assuming a constant pressure ratio, the maximum propagated instrument error, and the error due to the initial volume estimate is required to estimate the total error in calculating final mass in the tank. The following figure shows the mass in the tank at failure plotted versus blowdown, including error bars.

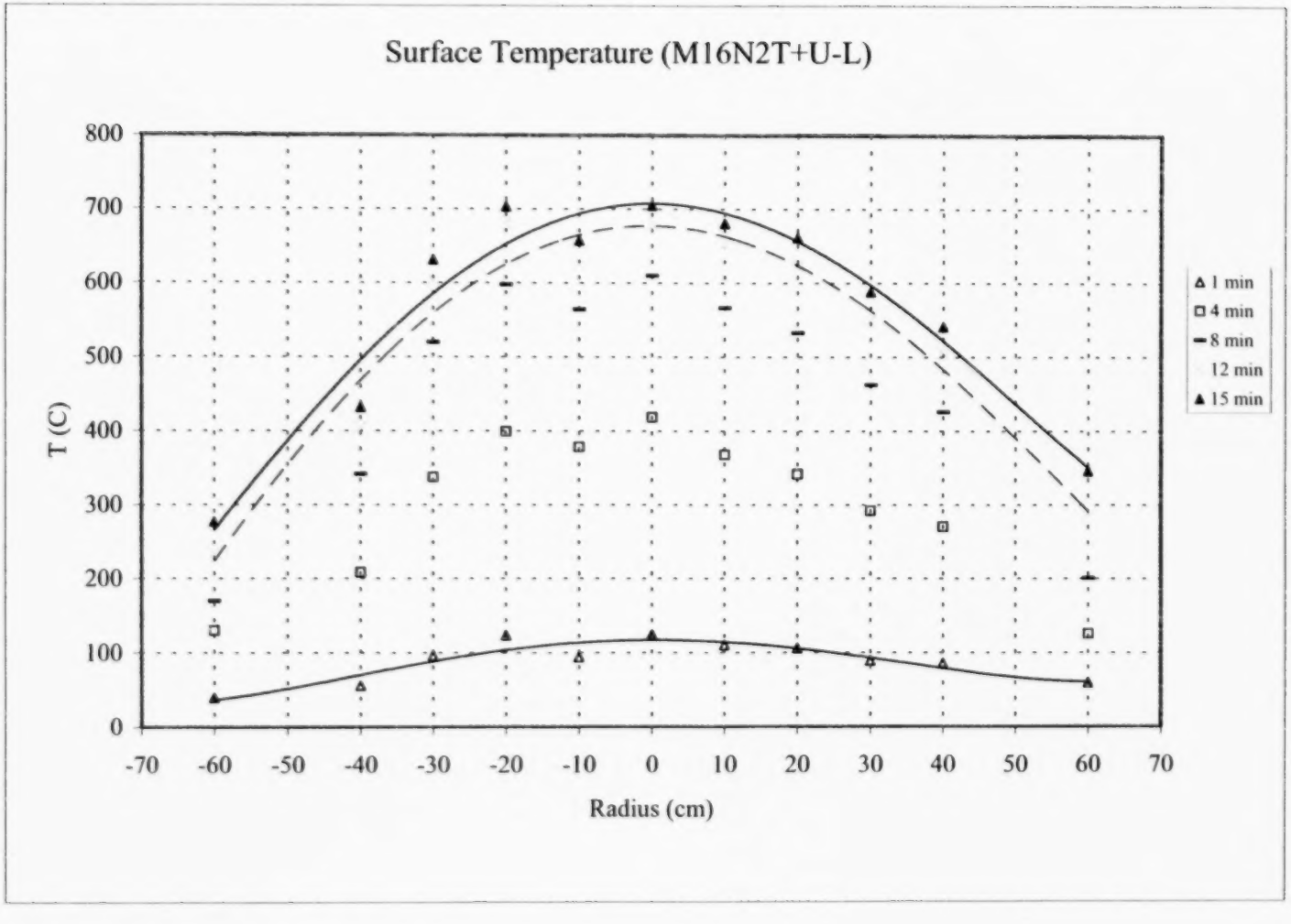


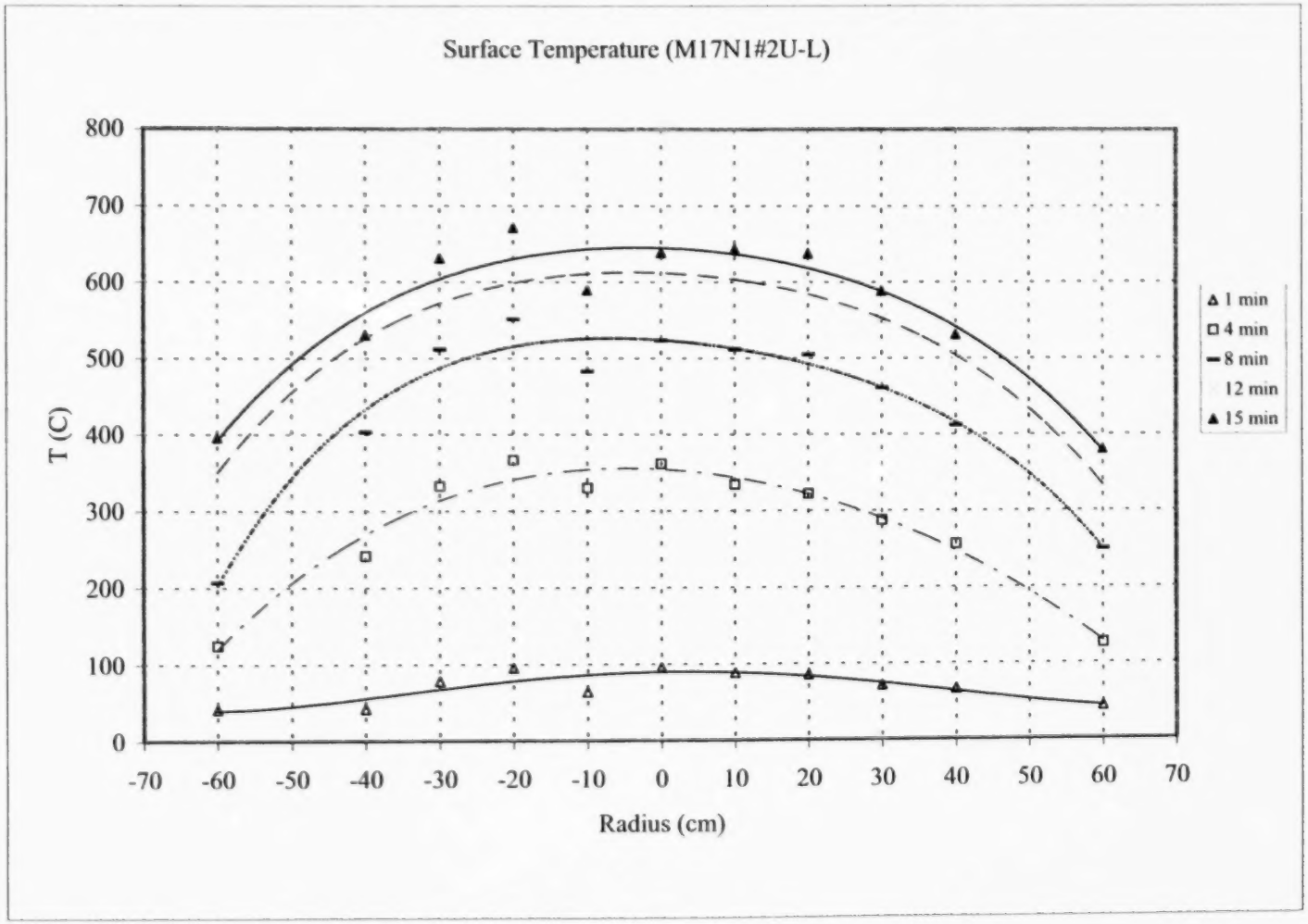
Mass in Tank at Failure versus Blowdown

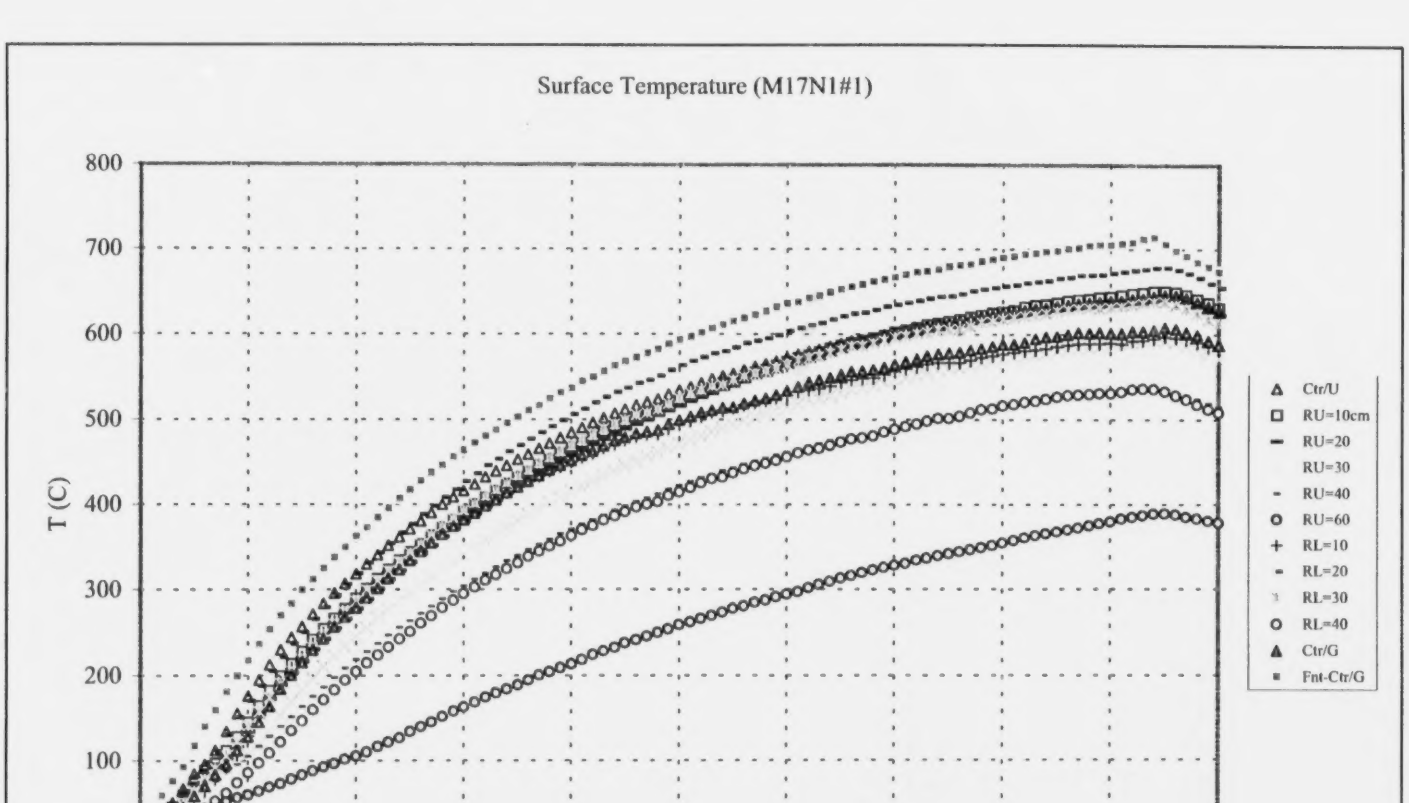
Appendix I: Burner Laboratory Tests

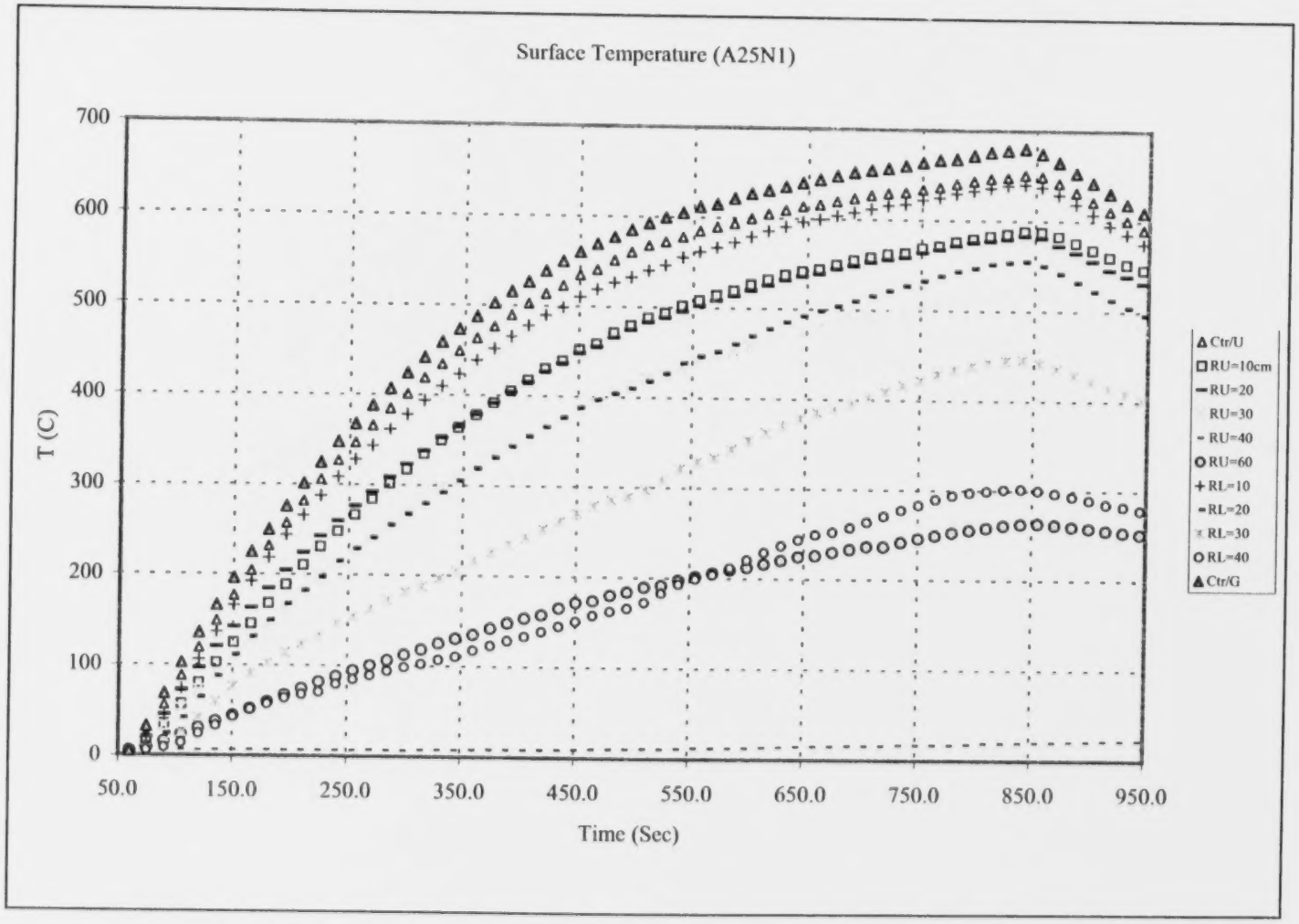
The following pages show the results from the burner laboratory tests. These tests were preformed prior to the field testing in order to better understand the burner behaviour and wall thermocouple installation.

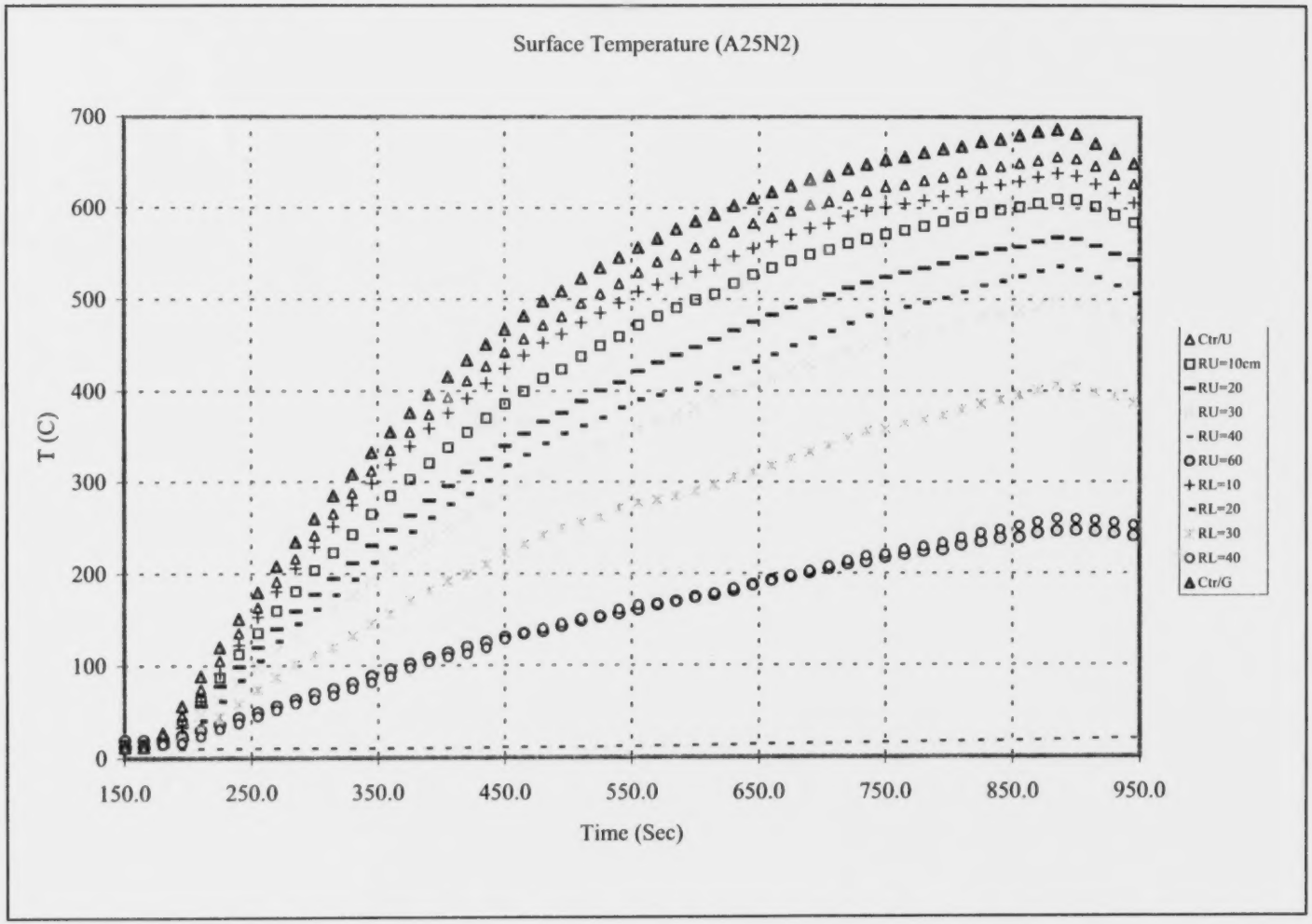

M16N`1#2UL
800
700
600
500
400
300
200
100
0
T (Celsius)
-70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70
Radius (cm)
1 min
4 min
8 min
12 min
15 min

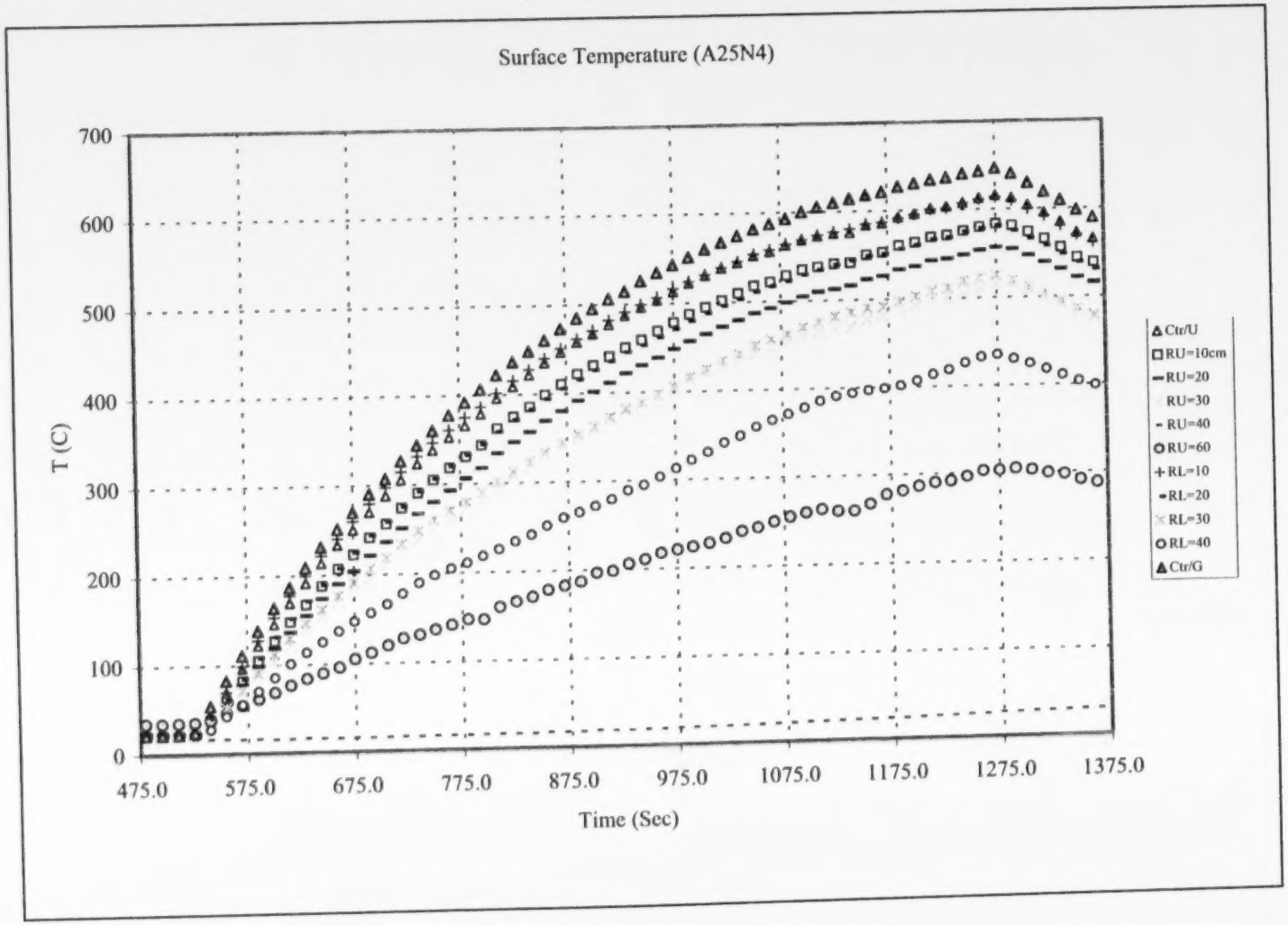

Surface Temperature (M16N2T+U-L)
T (C)
Radius (cm)
1 min
4 min
8 min
12 min
15 min
800
700
600
500
400
300
200
100
0
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70

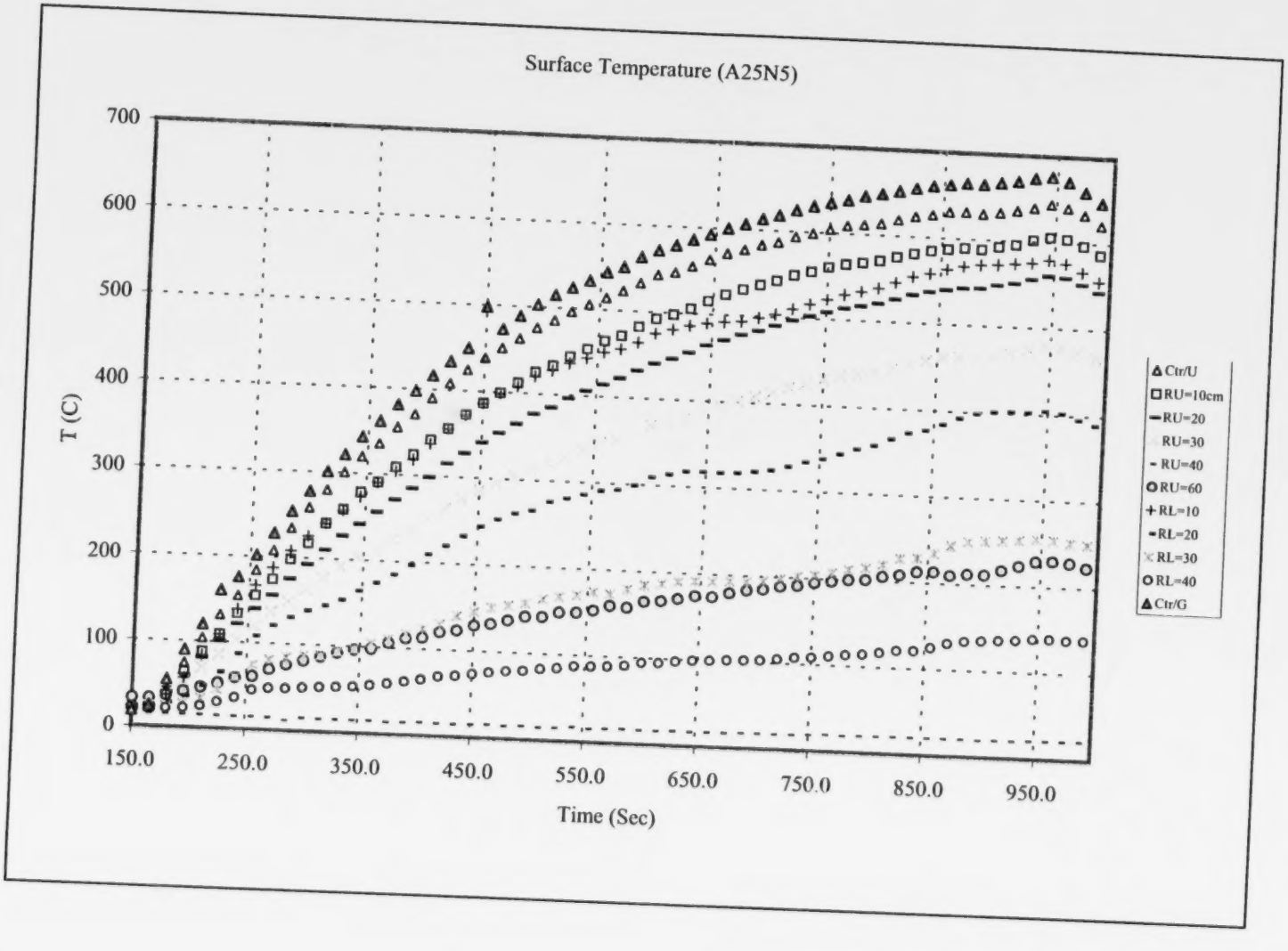

Surface Temperature (M17N1#2U-L)
T (C)
Radius (cm)
800
700
600
500
400
300
200
100
0
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
1 min
4 min
8 min
12 min
15 min

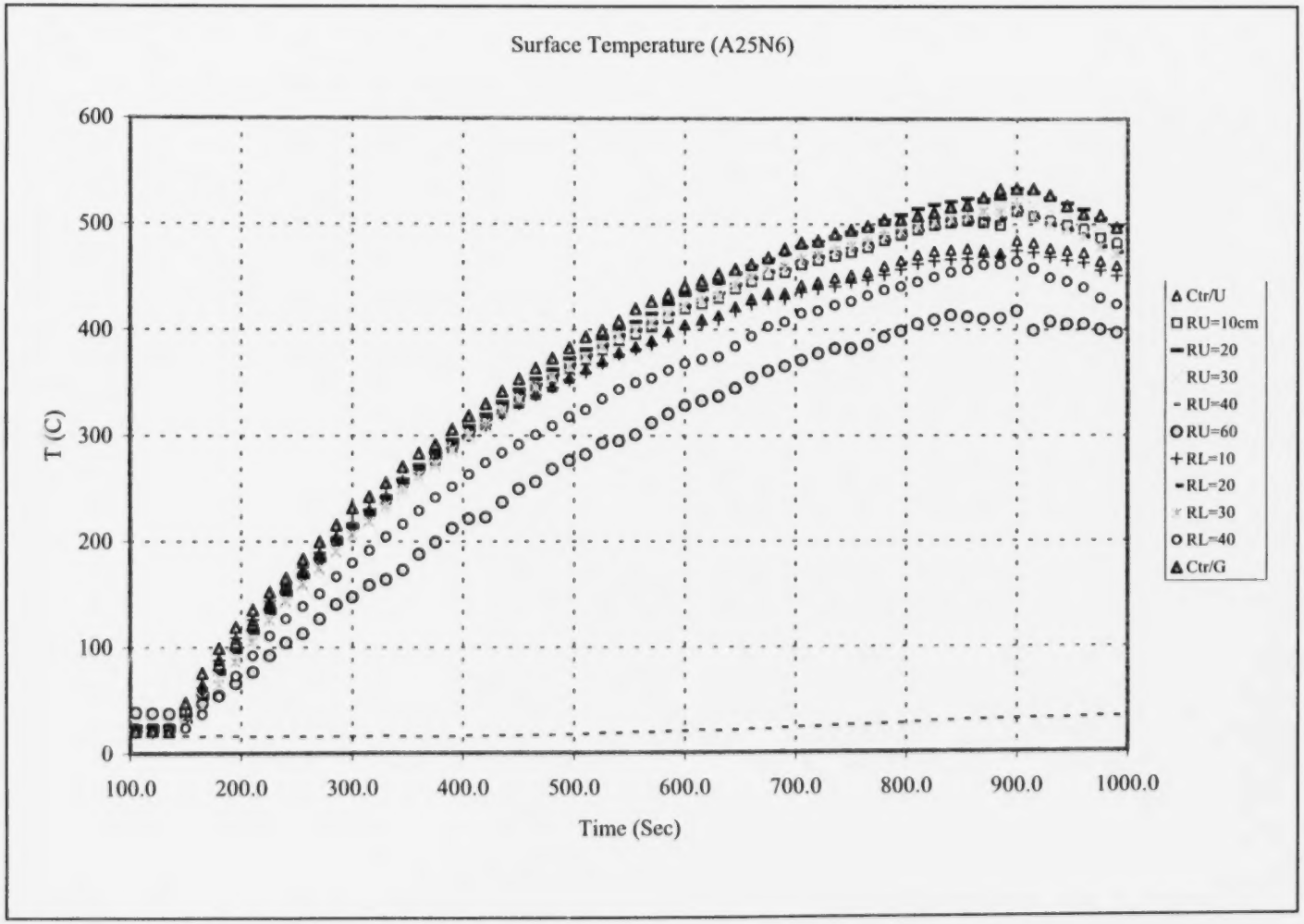

Surface Temperature (M17N1#1)
T (C)
Time (Sec)
0
100
200
300
400
500
600
700
800
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G
Fnt-Ctr/G

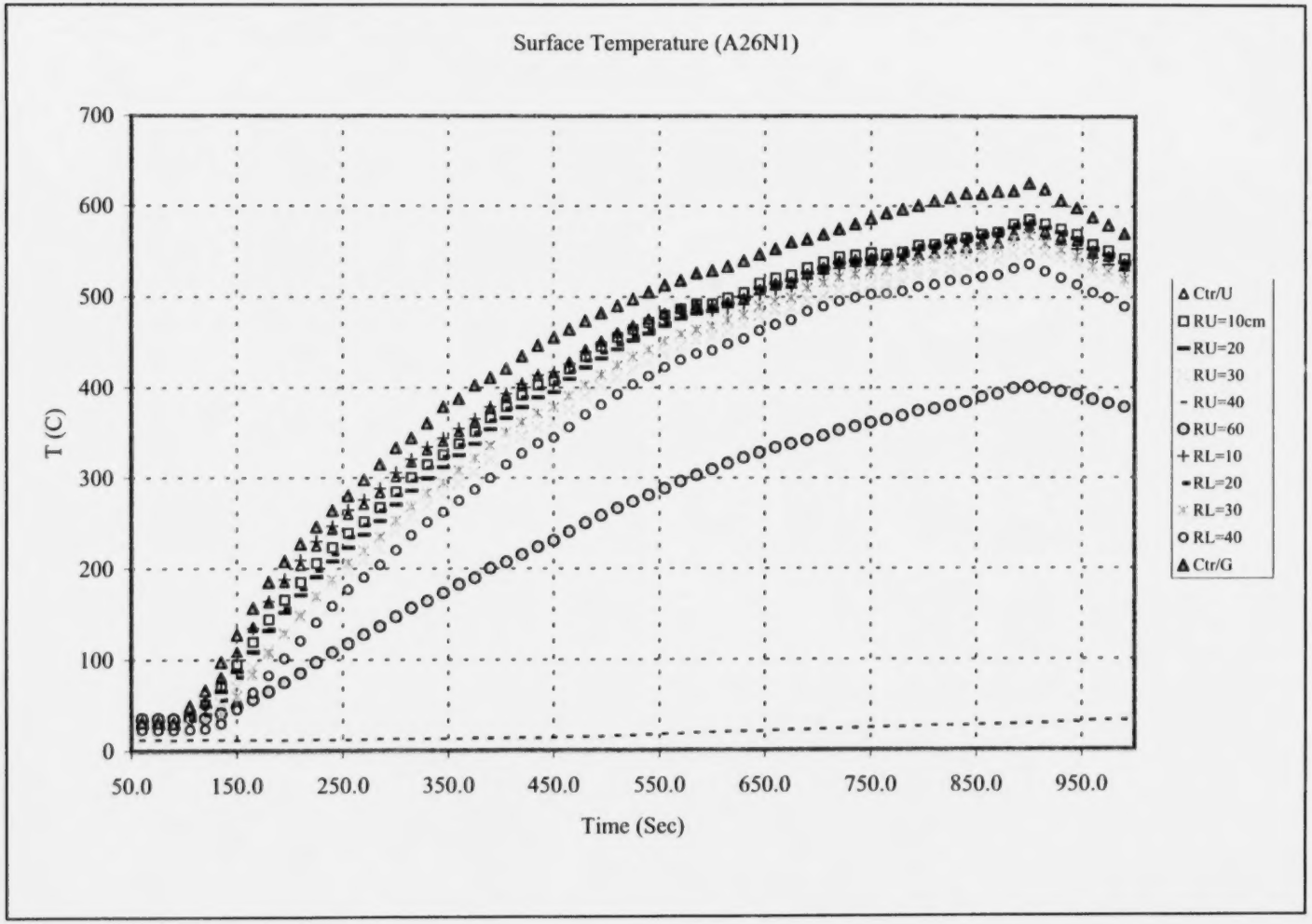

Surface Temperature (A25N1)
T (C)
Time (Sec)
700
600
500
400
300
200
100
0
50.0
150.0
250.0
350.0
450.0
550.0
650.0
750.0
850.0
950.0
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G

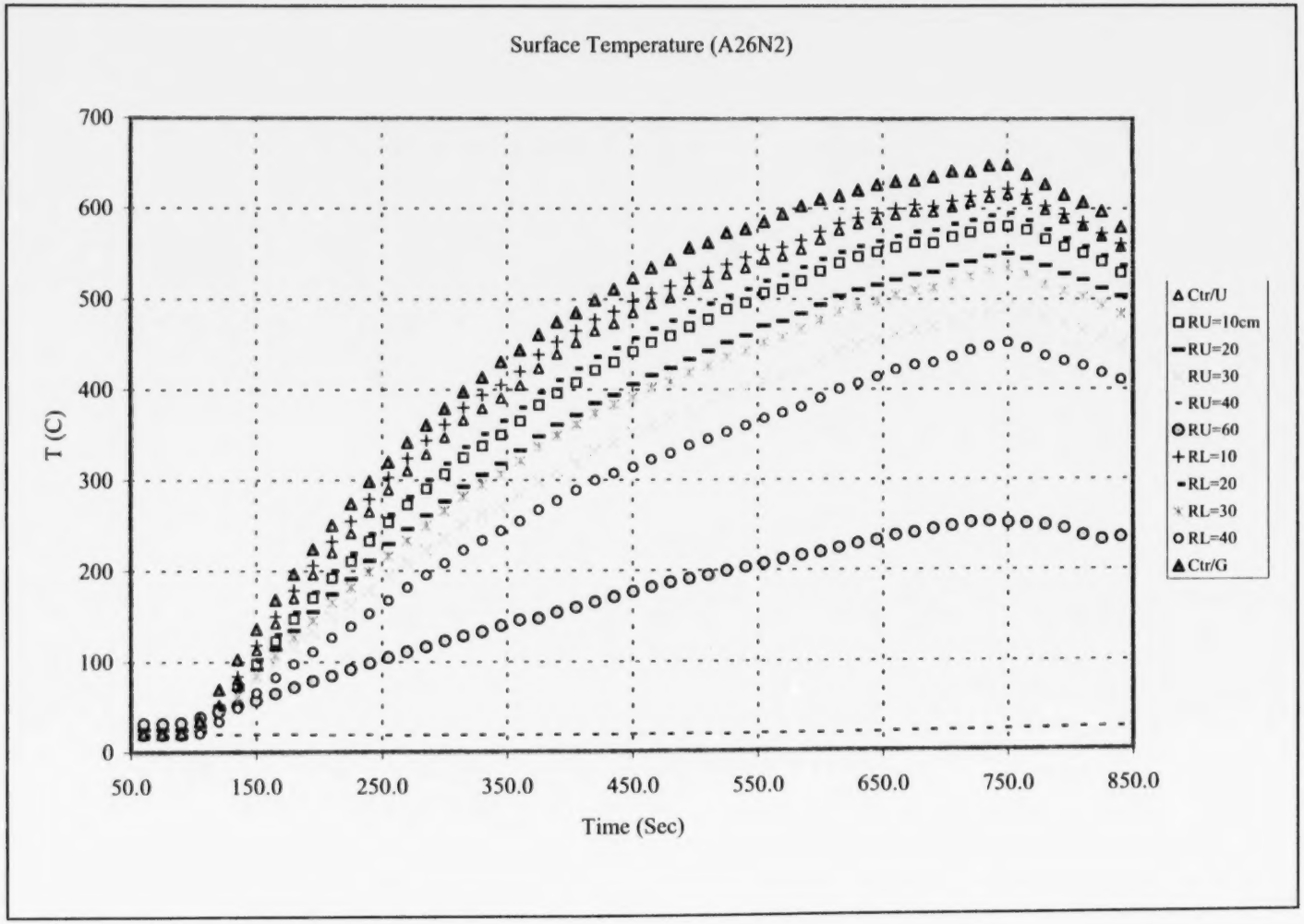

Surface Temperature (A25N2)
T (C)
Time (Sec)
700
600
500
400
300
200
100
0
150.0
250.0
350.0
450.0
550.0
650.0
750.0
850.0
950.0
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G

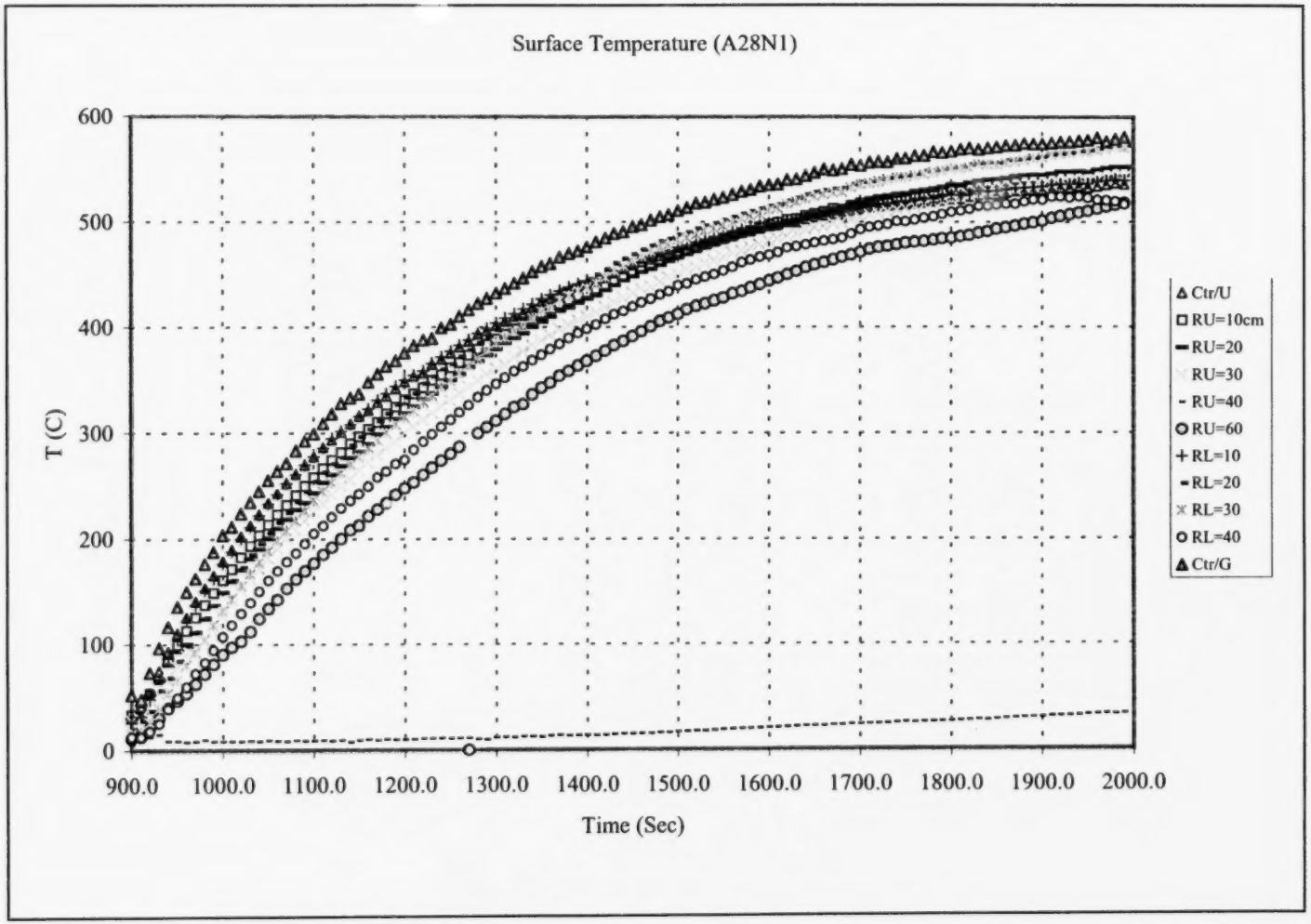

Surface Temperature (A25N4)
T (C)
Time (Sec)
700
600
500
400
300
200
100
0
475.0
575.0
675.0
775.0
875.0
975.0
1075.0
1175.0
1275.0
1375.0
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G

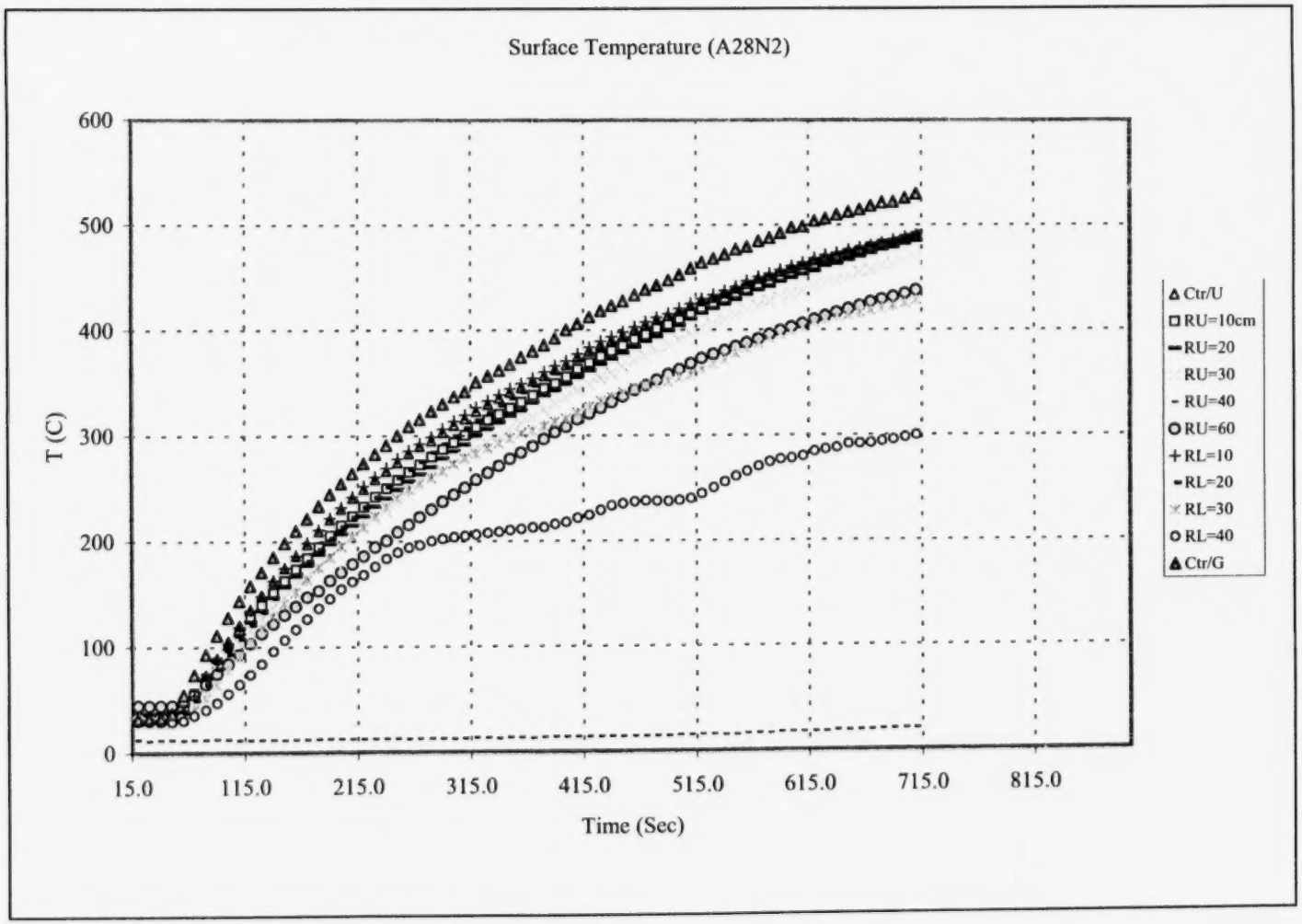

Surface Temperature (A25N5)
T (C)
Time (Sec)
700
600
500
400
300
200
100
0
150.0
250.0
350.0
450.0
550.0
650.0
750.0
850.0
950.0
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G


Surface Temperature (A25N6)
T (C)
Time (Sec)
600
500
400
300
200
100
0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G


Surface Temperature (A26N1)
T (C)
Time (Sec)
0
100
200
300
400
500
600
700
50.0
150.0
250.0
350.0
450.0
550.0
650.0
750.0
850.0
950.0
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G


Surface Temperature (A26N2)
T (C)
Time (Sec)
700
600
500
400
300
200
100
0
50.0
150.0
250.0
350.0
450.0
550.0
650.0
750.0
850.0
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G


Surface Temperature (A28N1)
T (C)
600
500
400
300
200
100
0
900.0
1000.0
1100.0
1200.0
1300.0
1400.0
1500.0
1600.0
1700.0
1800.0
1900.0
2000.0
Time (Sec)
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G


Surface Temperature (A28N2)
600
500
400
300
200
100
0
T (C)
15.0
115.0
215.0
315.0
415.0
515.0
615.0
715.0
815.0
Time (Sec)
Ctr/U
RU=10cm
RU=20
RU=30
RU=40
RU=60
RL=10
RL=20
RL=30
RL=40
Ctr/G

Appendix J: Data Acquisition Field Check Lists and Software User's Guide

The following pages contain check lists and the PRV Data Acquisition and Control Software User's Guide.

- System 200 Data Acquisition and Control Procedure
- Data Acquisition Channel Settings
- PRV Test Checklist
- High Speed Data Acquisition Checklist
- High Speed Camera Checklist
- Camera Checklist
- Bakker Card (BE) Settings
- V-Store 16 Tape Recorder Settings
- Instrumentation Settings

Pre-Test

1. Reinitialize all to default (operate menu).
2. Set all channel settings as required.
3. Start VI running.

All controls now active.

3. If saving to file is required press **save to file?**
4. Test controls
   a) PRV.
   b) burner valve.
   c) burner ignition.
   d) PRV shut-off.
   e) Video cameras
   f) SLR cameras
5. Press **Measurement** to begin measuring all channels
6. Verify measured data is correct.

Test Procedure

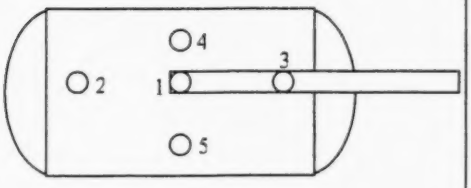
1. Turn on **PRV shut-off** (verify valve opens **3** times).
2. Turn on **igniters**.
3. Turn on **fuel valve**.
4. When ready to begin saving press **Start Recording.**
5. Turn off **igniters**.
6. When ready to begin recording on Racal press **Record**
7. Enable **PRV control**

ALL SWITCHES SHOULD BE GREEN.

Data Acquisition Channel Settings

Test			
Date		Time	
Directory			
File base			
Lading start channel		Pressure start channel	
Lading end channel		Pressure end channel	
Lading range		Pressure range	
Lading Scan Rate		Pressure Scan Rate	
Wall start channel		P1 s/n	
Wall end channel		P1 Location	
Wall range		P1 equation	
Wall Scan Rate		P2 s/n	
Fire start channel		P2 Location	
Fire end channel		P2 equation	
Fire range		Nozzle TC channel	
Fire Scan Rate		Nozzle TC range	
Air pressure ch		Nozzle Pressure ch	
		Nozzle Pressure range	
Air pressure range		Nozzle P s/n	
		Nozzle P eqn.	

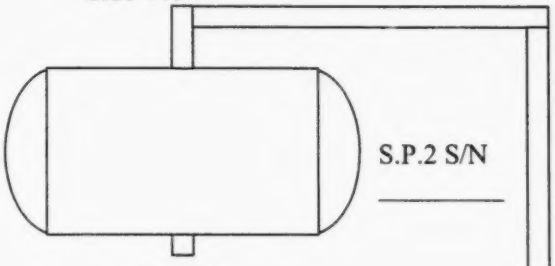
Top View



TC feedthrough numbering

1 _____
2 _____
3 _____
4 _____
5 _____

Side View



S.P.2 S/N _____

S.P.1 S/N _____

T.P. S/N _____

Notes:

_____

_____

_____

PRV Test Checklist

Test:

Date:

Relay Box					
Both cords of relay box plugged in					
PRV shut-off pluged in					
Igniters plugged in					
Burner valve plugged in (2)					
PRV auto plugged in light on					
PRV manual plugged in					
Air line					
Compressor plugged in					
Compressor on auto					
Ball valve at compressor open					
Ball valve at receiver open					
Pressure in Air line					
Auto PRV operates					
Manual PRV operates					
PRV shut-off operates					
Igniters					
Igniters operate					
Propane Fuel					
Tank Valves open					
Manual ball valve open					
Solenoid valve operates					
Final					
PRV ball valve open					

Checklist—High Speed Data Acquisition
BLEVE 2002

Date and Time:

Test:

Bakker Cards
- ☐ Turn computer on at least half hour prior to testing
- ☐ Check Connections
- ☐ Activate TEAM program for each card
- ☐ Load correct settings file
- ☐ Check trigger points
- ☐ Set to auto save
- ☐ Set to auto restart
- ☐ Set data file name to unique test identifier

16 Channel Racal Recorder
- ☐ Turn recorder on at least half hour prior to testing
- ☐ Check connections
- ☐ Put in tape. Make sure tape is in right position
- ☐ Check settings for channels being used
- ☐ Set Tape Speed (Does it give you enough time?)
- ☐ Check TTL connection

8 Channel Racal Recorder
- ☐ Turn recorder on at least half hour prior to testing
- ☐ Check connections
- ☐ Put in tape. Make sure tape is in right position
- ☐ Check settings for channels being used
- ☐ Set Tape Speed (Does it give you enough time?)
- ☐ Activate recording before leaving bunker

Instrumentation
- ☐ Check connections
- ☐ Check settings on amplifiers
- ☐ Make sure tape is on blast gauges
- ☐ Record serial number for each input channel

After Test
- ☐ Put all files in an appropriate directory
- ☐ Label and file tapes

Coordinate Times

Time on Bakker Card

Time on Watch

Time on V16

Time on V8

Comments

BLEVE Test Checklist (Cameras & HS DA)

Date:

Test:

Video Cameras

B1	B2	B3	Inst. Bunk.	
❑	❑	❑	❑	Check tape is in camera and rewound
❑	❑	❑	❑	Set to camera mode
❑	❑	❑	❑	Set zoom and aim
❑	❑	❑	❑	Set manual focus
❑	❑	❑	❑	Set to record date & time
❑	❑	❑	❑	**Put camera in record mode**

Still Cameras

B1	B2	B3	
❑	❑	❑	Turn cameras on
❑	❑	❑	Check film is in camera
❑	❑	❑	Set zoom and aim
❑	❑	❑	Set to fast picture taking mode
❑	❑	❑	Set manual exposure
❑	❑	❑	Set manual focus

High Speed Camera BLEVE Test Checklist

Date:

Test:

High Speed Camera

- ❑ Turn system on
- ❑ Check connections
- ❑ Check aim and focus
- ❑ Check settings (FPS, trigger point)
- ❑ Press *Ext Trig* button on front panel (Check display to ensure it engages)
- ❑ Press *Rec* button

Settings

Frames per Second: _____

Shutter Speed: _____

Trigger Point (%): _____

Record Time: _____

Pre-trigger record time: _____

BE Settings

Date and Test

Two Boards:

BE 490 Settings

02PRV490.set
Pressure Trans.

Parameter	Setting
Base Address	300 hex
Number of Channels	2
Input Span	10 V
Scaling 1 Volt =	6.897 kPa
Memory	65536
Pre-Trigger	8000
Post-Trigger	57536
Trigger	Ch 1 and Ch 2
	Internal Alarm
	+/- 3.233
Storage	Test Dependant

BE 494 Settings

02PRV494.set
Blast Gauge

Parameter	Setting
Base Address	310 hex
Number of Channels	5
Input Span	10 V
Scaling 1 Volt =	6.897 kPa
Memory	16384
Pre-Trigger	3000
Post-Trigger	13384
Trigger	Ch 2
	Internal Alarm
	+/- 3.233
Storage	Test Dependant

V-Store16 Settings

Date and Time

Test

Machine State Page

Parameter	Setting
Flutter	OFF
Speed Ref.	INT
Audio Warning	1
Cassette	T160
Power Save	OFF
File Number	

Other Settings

Speed	15 in/s
Play Time	14.30 min
Rec. Freq.	50 kHz

if Speed	then Freq.	Play Time
3.75	12.5	57
7.5	25	29
15	50	14
30	100	7

Channel State Page

	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7	Channel 8
Parameter	**Setting**	**Setting**	**Setting**	**Setting**	**Setting**	**Setting**	**Setting**	**Setting**
I/P Atten	TIM	N/A	5V	5V	5V	5V	5V	5V
Record Enable	ON	OFF	ON	ON	ON	ON	ON	ON
Calibration Signal	N/A	N/A	OFF	OFF	OFF	OFF	OFF	OFF
Bandwidth	N/A	N/A	WB2	WB2	WB2	WB2	WB2	WB2
I/P Offset	N/A	N/A	OFF	OFF	OFF	OFF	OFF	OFF
Unipolar	N/A	N/A	OFF	OFF	OFF	OFF	OFF	OFF
Filter	N/A	N/A	TCH	TCH	TCH	TCH	TCH	TCH
Instrument:	**Timer (None)**	**None**	**Blast Gauge**	**Blast Gauge**	**Blast Gauge**	**Blast Gauge**	**Blast Gauge**	**Blast Gauge**

V-Store16 Settings (cont.)

Channel State Page

	Channel 9	Channel 10	Channel 11	Channel 12	Channel 13	Channel 14	Channel 15	Channel 16
Parameter	**Setting**	**Setting**	**Setting**	**Setting**	**Setting**	**Setting**	**Setting**	**Setting**
I/P Atten	5 V	N/A	N/A	N/A	N/A	N/A	5 V	N/A
Record Enable	ON	OFF	OFF	OFF	OFF	OFF	ON	OFF
Calibration Signal	OFF	N/A	N/A	N/A	N/A	N/A	OFF	N/A
Bandwidth	WB2	N/A	N/A	N/A	N/A	N/A	WB2	N/A
I/P Offset	OFF	N/A	N/A	N/A	N/A	N/A	OFF	N/A
Unipolar	OFF	N/A	N/A	N/A	N/A	N/A	OFF	N/A
Filter	TCH	N/A	N/A	N/A	N/A	N/A	TCH	N/A
Instrument:	**Transient P**	**None**	**None**	**None**	**None**	**None**	**Static P**	**None**

Radiometer

Date:

Test:

Parameter	Value	Notes
Input Range	0 to1360 kW/m^2	120 BTU/(ft*ft*s)
Output Range	10mV	
Output/Input	0.007353mV/(kW/m^2)	Approximate
		--See Calibration Sheets
Recording Freq.	25 kHz	Racal Recorder
		Bakker Card not used
Required Duration	6 sec	Based on1993 tests
Required Input Range	300 kW/m^2	Based on1993 tests
Required Output Range	2.2 mV	
Max. Expected Input	600 kW/m^2	Conservative Guess
Max. Expected Output	4.4 mV	
Amp. Setting	x1000	
Recorder Input Range	4.4 V	

Hy-cal Radiometers
Model R-2059-A-120-72

S/N	V-8
922088	
922089	
922090	
941311	
941312	
941313	

Transient Pressure Transducer

Date:

Test:

Parameter	Value	Notes
Input Range	+\- 34.5 MPa	5000 psi
Output Range	+\- 5V	After Charge Converter
Output/Input	0.14504 mV/kPa	1mV/pC
Recording Freq.	100 kHz	Racal Recorder
	Channel 1 and 2	BE 490
Required Duration	50 ms	Based on1993 tests
Required Input Range	15 MPa	Based on1993 tests
Required Output Range	2.2 V	
Max. Expected Input	30 MPa	Conservative Guess
Max. Expected Output	4.4 V	
Amp. Setting	x1	
Recorder Input Range	4.4V	

PCB Transient Pressure Transducer
Model 112A05

S/N	V-16	BE 490
10694		
10784		
10786		
11636		
11637		
11638		
11639		
11646		
11648		
11649		
11650		
11651		

PCB Charge Amplifier
Model 422D03

S/N	V-16	BE 490
5149		
5150		

Blast Gauges

Date:

Test:

Parameter	Value	Notes
Input Range	+/- 345 kPa	
Output Range	+/- 5V	
Output/Input	14.5 mV/kPa	
Recording Freq.	100 kHz	Racal Recorder
	Channel 2,3,4, and 5	BE 494
Required Duration	200 ms	Based on1993 tests
Required Input Range	14 kPa	Based on1993 tests
Required Output Range	0.2 V	
Max. Expected Input	28 kPa	Conservative Guess
Max. Expected Output	0.4V	
Amp. Setting	x10	
Recorder Input Range	4V	

PCB Blast Gauge
Model 137A23

S/N	V-16	BE 494
1901		
1968		
2927		
2934		
2935		
2936		

PRV Data Acquisition and Control Software
User's Guide

By

Mark Cunningham

September, 2000.

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Appendix 1 : Sub-VI Listing

Introduction

PRV_DAQII is a data acquisition and control program that was written for the Queen's University Propane Fire Tests of Tests of August-September 2000. The program is used to remotely carry out the fire testing of propane tanks and collect temperature and pressure data during the tests.

PRV_DAQII, written using LabView 5.0, was developed specifically for the Sciemetrics System 200 data acquisition system.

System Requirements

The following hardware requirements are recommended for PRV_DAQII

1. *PIII 550* – the system can be used on a lower systems, but data acquisition rates may have to be decreased
2. *Windows 95 or 98* – the System 200 is accessed by directly reading the system memory at the interface card's base address. Windows NT does not allow the system memory to be directly addressed.
3. *1024 X 768 resolution* – the display screen was designed to be used at this resolution

General Layout of PRV_DAQ

PRV_DAQII contains both a control and data acquisition component. The control component consists of a series of toggle switches that allow various functions on the test site to be controlled remotely through the solid state relays in the System 200. The control system also includes the dead band control of a pneumatic Pressure Relief Valve. Pressure transducers on the tank supply the input for the control routine which controls the output state of the valve through a solid state relay.

The data acquisition is divided into the following 5 separate tasks:

i) Lading temperature
ii) Wall temperature
iii) Fire temperature
iv) Tank pressure
v) Nozzle temperature and pressure
vi) Pneumatic line pressure

The scan rate of each task can be different and therefore based on the type of instrument included in the task. These tasks can be executed in a measurement only mode as well as a measure and save to disk mode. The data is saved to disk after each sample and is not buffered in memory.

Screen Layout

The PRV_DAQII screen consists of three main areas, which are described below :

1. Switch control
   b) Location – right hand side of upper portion of the screen
   c) Used to :
      i) Turn the measurement of channels on/off
      ii) Enable/disable the automatic control of the PRV
      iii) Turn saving on/off
      iv) Control relays for
         (1) Fuel line valve
         (2) Ignitors
         (3) Prv shut-off valve
      v) Run PRV test – pulses PRV valve three times
      vi) Control record/stop of the tape recorder

2. DAQ display
   a) Location - the left hand side of the upper portion of the screen
   b) Contains
      i) three plots displaying :
         (1) Tank pressure
         (2) Lading temperature
         (3) Wall temperature
      ii) Switch showing current position of PRV
      iii) Boxes for setting PRV open and close pressure.

iv) Boolean switches to indicate which pressures are to be used for PRV control
v) Table displaying fire temperatures
vi) Boxes displaying
(1) Tank pressures
(2) Nozzle temperature
(3) Nozzle pressure
(4) Pressure of pneumatic line
(5) Reference temperature for thermocouple junctions

3. Settings
a) Location - lower portion of the screen
b) Contains settings for the following data acquisition tasks:
i) Lading temperature
ii) Wall temperature
iii) Fire temperature
iv) Tank pressure
v) Nozzle temperature and pressure
vi) Pneumatic line pressure
c) Settings for file directory and file name prefix.

Using PRV_DAQII

The following are instructions for operating PRV_DAQII :

Start-up

1. double click on the PRV_DAQII icon or start LabView and open PRV_DAQII.
2. In some cases it may be required to manually find some files. A dialogue box will prompt for their locations

Set-up

Once the program is started, the settings for the data acquisition and control must be set if different from the current default values. Unless indicated, the settings cannot be changed while the PRV_DAQII VI is running. If settings are to be changed, stop the VI, change the settings and re-start the VI.

The following describes each setting which can be adjusted

1. File Set-up
   a) File directory – the directory name to which the files are to be saved. The directory must already exist or LabView will give an error
   b) Run name - the name of the current run that will be used as the root for all file names. The file names have the format *run-name task-name.dat*.
2. Lading Temperature
   a) Lading temperature scan rate – rate at which the lading temperature channels will be scanned and saved in samples per second.
   b) 1st TCP channel – number of the first channel to be scanned in the lading thermocouple task.
   c) Last TCP channel – number of the last channel to be scanned in the lading thermocouple task.
   d) Lading TCP range – the voltage range to be used for measuring the lading thermocouple channels

Note : all lading temperature channels must be in consecutive order on the D/A board

3. Wall Temperature
   a) Wall temperature scan rate – rate at which the wall temperature channels will be scanned and saved in samples per second.
   b) 1st TCP channel – number of the first channel to be scanned in the wall thermocouple task.
   c) Last TCP channel – number of the last channel to be scanned in the wall thermocouple task.
   d) Lading TCP range – the voltage range to be used for measuring the wall thermocouple channels

Note : all wall temperature channels must be in consecutive order on the D/A board

4. Fire Temperature
   a) Fire temperature scan rate – rate at which the fire temperature channels will be scanned and saved in samples per second.
   b) 1st TCP channel – number of the first channel to be scanned in the fire thermocouple task.

c) Last TCP channel – number of the last channel to be scanned in the fire thermocouple task.
d) Lading TCP range – the voltage range to be used for measuring the fire thermocouple channels

Note : all fire temperature channels must be in consecutive order on the D/A board

5. Pressure and PRV
   a) PRV relay channel – channel on the 222 board from which the solenoid for the PRV is controlled
   b) Tank Static Pressure Scan Rate – rate at which the tank pressure channels will be scanned and saved in samples per second. The PRV control loop also executes at this rate
   c) 1st pressure channel – number of the first channel to be scanned in the pressure and PRV task.
   d) Last pressure channel – number of the last channel to be scanned in pressure and PRV task.
   e) Pressure range – the voltage range to be used for measuring the pressure and PRV channels
   f) Calib Coefficients – the linear calibration coefficients for each pressure transducer in the form of $Pressure = a \cdot volts + b$
6. Mass Flow Nozzle
   a) Nozzle Scan Rate - rate at which the nozzle channels will be scanned and saved in samples per second.
   b) Nozzle TCP range – the voltage range to be used for measuring the nozzle thermocouple.
   c) Nozzle TCP channel – channel number to which the nozzle thermocouple is connected
   d) Nozzle P range – the voltage range to be used for measuring the nozzle pressure
   e) Nozzle P channel – channel number to which the nozzle pressure transducer is connected
   f) Nozzle Calib Coefficients - the linear calibration coefficients for the nozzle pressure transducer in the form of $Pressure = a \cdot volts + b$
7. Pneumatic Pressure Set-Up
   a) Air P range – the voltage range to be used for measuring the pneumatic pressure
   b) Air P channel – channel number to which the pneumatic pressure transducer is connected
   c) Air Calib Coefficients - the linear calibration coefficients for the pneumatic pressure transducer in the form of $Pressure = a \cdot volts + b$
8. PRV control (top right of screen)
   a) PRV Open Pressure – pressure in calibrated units which the PRV valve will open in dead band control. The value of the open pressure can be changed while the test is running.
   b) PRV Close Pressure – pressure in calibrated units at which the PRV valve will close in dead band control. The value of the close pressure can be changed while the test is running.
   c) Use P – indicates which pressure transducer(s) will be used as an input into the dead band control loop. The pressure transducer with the lowest channel number

is at the top. A black square indicates that the pressure transducer will be used in the dead band control. If more than one transducer is indicated, the arithmetic mean of the pressure readings is used for the PRV control. The transducers used in the average can be changed during while the test is running.

9. Channels to plot
   a) In the arrays at the right of the lading and wall temperature enter the number of the lading or wall temperatures that are to be plotted. These numbers are of the thermocouples in the tasks starting at 0 and going upwards, and not the channel number.

Fixed Settings

Some settings have been set within the program and cannot be set in the front panel. The channels that are fixed are outlined in the table below:

Function	Board	Channel
PRV shut-off valve	222	2
Ignitors	222	3
Fuel line valve	222	4
Racal Stop indicator	210	0 digin
Racal Record indicator	210	1 digin
Racal Stop button	210	0 digout
Racal Record button	210	1 digout

Running PRV_DAQII

Once the settings have been set, the following steps must be executed in sequence.

Pre-test Sequence

1. Ensure that all switches on the left hand side are off. All buttons should be red except "ignitors" which should be green.
2. Start PRV_DAQII running by pressing the run arrow on the left side of the LabView toolbar. All the control switches are now active.
3. If data is to be saved in the current session change the *Save to File* button to *Yes*.
4. To start measuring all of the channel values change the *Measurement* button to *Yes*. The test time clock is set to zero and the data in the plots cleared.

Test Sequence

5. Close PRV shut-off valve by clicking the *PRV shut-off* toggle switch. The toggle switch is green when the valve is closed.
6. Open fuel line valve by clicking on *Fuel Line Valve* toggle switch. The toggle switch is green when the valve is on.
7. Start recording to file by clicking on *Start Recording* and changing it to *Yes*. The test time clock is set to zero and the data in the plots cleared.

8. Ignite the burners by clicking on the ignitors toggle switch. The toggle switch is red when the ignitors are operating. Turn off the ignitors as soon as all of the burners are lit.
9. Once the ignitors are off, change the PRV control to enable. Do not change to enable until the ignitors are off since the ignitors may cause spikes in the pressure transducer readings resulting in premature opening of the PRV.
10. At the pre-determined delay, start the Racal recorder recording by pressing the square *REC* button. The LED above the *REC* button should turn green. The recorder can be stopped and restarted at any time by pressing the *STOP* or *REC* buttons.

Note : During a test all the buttons should be green if controls are in the correct postion.

11. To stop recording data click on the *Start Recording* button to turn it *off*.
12. To stop measuring data values, click on the *Measurement* button to turn it *off*.

Program Structure

In PRV_DAQII, all access to the System 200 boards is done through the 802 interface cards using basic library routines contained in lv200.dll. The program calls sub VI's that contain the *Call Library* function of LabView to call the functions in the DLL. All higher level programming is done within Labview.

Sub VI's have been used for repetitive tasks or to simplify the layout of the program.

LV200.dll

LV200.dll contains all of the command routines required for communicating with the 236, 210, and 222 boards in the System 200 chasis. The DLL was written in C++ and is based on the Level 1 C drivers supplied by Sciemetrics. The DLL was compiled as a DLL project using Visual C++ 6.0. The variable types in the original C drivers were changed to allow the DLL to be used on a 32 bit computer rather than a 16 bit architecture for which they were originally written.

LV200.dll contains the following function calls:

```
int reset222(unsigned badd);
int read222 (unsigned badd, int chan, int *state);
int write222 (unsigned badd, int chan, int state);
int init236 (unsigned badd);
int voltshlg236 (unsigned badd, int chan, int range, int
HorL,
                        int AZflag,int az236[4], float
                        *volts);
int volts236 (unsigned badd, int chan, int range, int
AZflag,
                        int az236[4],float *volts);
int tablevolts236 (unsigned badd, int size, int chans[],
int range,
                        int AZflag, int az236[4],float
                    volts[]);
int autozero236 (unsigned badd, int zeros[]);
int interthmst236 (unsigned badd, float *ohms);
int readdin210 (unsigned badd, int chan, int *state);
int readdout210 (unsigned badd, int chan, int *state);
int writedout210 (unsigned badd, int chan, int state);
int out210counts (unsigned badd, int chan, int dtoacount);
int checkbaddid(unsigned badd, int modelnumber);
int checkid(unsigned badd);
```

The purpose of the above function calls is described in the Level 1 software documentation.

Sub VI's

Labview programming makes use of sub-VI's which are similar to subroutines or functions in Fortran. Two types of subroutines have been used in PRV_DAQII :

1. interface sub-VI's- These sub-VI's provided an interface to the functions contained in lv200.dll using the Call Library function.
2. Programming sub-VI's - Several sub-VI's have been created for various tasks including creating TecPlot file headers, and dead band control for the PRV etc. These sub-VI's simplify repetitive tasks and make the overall code more readable.

A full listing of the sub-VI's and their function is included in Appendix 1.

Graphical Programming Layout

The graphical programming in the LabView diagram window of PRV_DAQII is laid out in three main units which use a combination of while loops and sequences to carry out the data acquisition and control.

1. file set-up – if the data is to be saved to file the files are opened and initialized with TecPlot headers.
2. Data acquisition – The data acquisition is set-up with five main tasks
   a) lading temperature
   b) wall temperature
   c) fire temperature
   d) tank pressure and PRV control
   e) nozzle temperature and pressure

   Each task is contained in a while loop that executes at the rate set by sample frequency for the task. For high-speed data acquisition, if any task contains more than one channel with the same settings, the tablevolts function is used. The method currently used to scan the channels with tablevolts requires that the channels be in consecutive order. This is a result of the LabView programming. The LV200.dll function can take channels in any order.
3. Switch control – several relays and digital inputs/outputs are used to control the Racal tape recorder, burner fuel valve, ignitors, and PRV shut-off valve. These controls are contained in a while loop that executes two times a second. The slightly long delay makes the system a little sluggish but prevents the system from becoming bogged down. At each execution of the loop the position of the control switches are checked and action is taken as appropriate.

Timing

The System 200 does not have the capability to sample at accurate intervals. In PRV_DAQ the timing of the sampling for each task is controlled by the wait Sub-VI included in each while loop. Each loop will wait the required delay and then attempt to carry out the data acquisition or control task. Since there are several tasks running simultaneously, LabView semaphores are used to ensure that only one task is accessing the boards in the System 200 at any one time. By using semaphores, when a task wants to access a board, a request for access is issued. If no other tasks are accessing the board, the task is allowed immediate access. If one or more requests for access are in line ahead, the task waits until the board is free.

Due to this requirement, the execution frequency will not necessarily be constant. Therefore, the time of acquisition is included in the data file.

Thermocouples

The voltages read by the System 200 are converted to temperature using the NIST thermocouple polynomials in a conversion VI adapted from a LabView supplied VI. The reference temperature at the thermocouple junction at the DA board is measured by an internal thermistor mounted on the 236 board. To increase the DA capacity, this temperature is only read at a specified interval and not when every time a thermocouple voltage is read. Currently the internal reference temperature is updated once per minute. This was found to be adequate for the rate at which the temperature in the System 200 changed. The update frequency of the reference temperature can be changed by changing the rate at which the while loop that reads the reference temperature executes.

File output format

One data file is saved for each DA task using the run name as a prefix. The files are named as follows :

Lading temperature file	-	*run-name*lading.dat
Wall temperature file	-	*run-name*wall.dat
Fire temperature file	-	*run-name*firet.dat
Tank pressure file	-	*run-name*tankp.dat
Nozzle data file	-	*run-name*massflow.dat

All data files are saved with a TecPlot header that allows them to be plotted immediately. The header contains the title of the plot and variable names. The time of acquisition of each sample is listed in the leftmost column in each file. A sample of a file is shown below:

```
Title ="tankp"
Variables ="time (s)" "tankp 0" "tankp 1" "valve position"
Zone F=Point
0.080     113.722   114.839   0.000
0.179     113.722   115.220   0.000
0.281     113.722   115.220   0.000
```

Test Programs

Several test programs have been written to allow measurement and control to be done separately from PRV_DAQII. These are useful for diagnostics and testing individual components of the system. These are described in Appendix 1.

Appendix 1

Sub VI Listing

Interface Sub-VI's

Autozero.vi – measures the autozero values of the 236 board
Badd 210.vi – contains the global variable of the base address for the 210 board
Badd 212.vi – contains the global variable of the base address for the 212 board
Badd 236.vi – contains the global variable of the base address for the 236 board
Checkbaddid.vi – checks that the board at badd XXX has the expected number
Checkid.vi – checks the number of a board at the given base address
Init236.vi – carries out initialization of the 236 board
Interthermst236.vi – reads the temperature of the internal thermistor on the 236 board
Interthermst236synch.vi – same as Interthermst236.vi using semaphores
Out210counts.vi – outputs a analogue to digital count to the 210 board
Read222.vi – reads the state of a relay on the 222 board
Read222synch.vi – same as Read222.vi using semaphores
Readdin210.vi – reads the state of a digital input on the 210 board
Readdout210.vi – reads the state of a digital output on the 210 board
Reset222.vi – resets all of the relays on the 222 board to off
Tabletcp.vi – reads an array of thermocouples on the 236 board
Tabletcpsynch.vi – same as Tabletcp.vi using semaphores
TableVolts236.vi – reads an array of voltages on the 236 board
TableVolts236synch.vi – same as TableVolts236.vi using semaphores
Thermocouple.vi – reads a single temperature from the 236 board
Volts236.vi – reads a single differential voltage from the 236 board
Volts236synch.vi – same as Volts236.vi using semaphores
voltshlg236.vi – reads a single voltage between high and ground or low and ground on the 236 board
write222.vi – write the state to a relay on the 222 board
write222synch.vi – same as write222.vi using semaphores
writedout210.vi – writes the state to a digital output on the 210 board

Utility Programs

Channel array.vi – creates an array of channel numbers given the first and last channel number in a string of consecutives channels
Fileopen.vi – opens a file with a TecPlot header
NIST TCP buffer.vi – uses NIST polynomials to convert a table of voltages to temperature
NIST Thermocouple.vi - uses NIST polynomials to convert a voltage to temperature
P average.vi – averages pressures for use in the PRV control
PRVcontrol.vi – controls the state of the PRV using deadband control
PRVcontrolsynch.vi – same as PRVcontrol.vi using semaphores
PRVtest.vi – cycles the PRV three times
Racal.vi – controls the stop and record functions of the tape recorder
Single P convert.vi – converts a single voltage to pressure using a linear fit
Static P convert.vi – converts a table of voltages to pressure using linear fits

Tcpconvert.vi – converts a thermocouple voltage to temperature
TecPlot header.vi – writes a TecPlot header to file
Tforchart.vi – creates a sub-array for plotting
Variable name.vi – generates the variables names for an array of channels

Test Programs

Digoutcontrol.vi – switches the digital outputs on the 210 board
PRVcycletest.vit – cycles the PRV at a specified rate
Racalrun.vi – runs the control of the Racal recorder
Relaytest.vi – allows control of all the relays on the 222 board
Tabletcptest.vi – allows an array of thermocouples to be read at a specified frequency
Thermocoupletes.vi – allows a thermocouple to be read at a specified frequency
Volttest.vi – allows a voltage to be read at a specified frequency